CONVERTER SIMULATION FOR HVDC TRANSMISSION

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by
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CERTIFICATE

Certified that the work entitled "Converter Simulation for HVDC Transmission" by Mr. V.V. Suryanarayana has been carried out under my supervision and has not been submitted elsewhere for the award of a degree.

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CONTENTS

ABSTRACT

This thesis deals with the digital simulation of three phase bridge converter. A detailed representation of converter is considered and the mathematical model is developed. The generalized equations, describing the state of the converter, are derived on the basis of topological considerations. These equations can take care of all possible modes of converter operation, where the DC link current is continuous. The generalized equations are presented in a form that can be easily implemented on a digital computer. Computer program for converter simulation is developed and is used to analyse the disturbances in a two terminal HVDC transmission system. In particular, prediction of overcurrents and overvoltages caused by the commutation failure and continuous misfire in the inverter are given as examples of the application of this program.

CHAPTER 1

INTRODUCTION

1.1 GROWTH OF HVDC SYSTEMS

Direct current transmission is one of the exciting technical developments in the last two decades. It was initiated when the 20 MW Gotland-Sweden line was commissioned in 1954. With this modest beginning, DC transmission has grown in the present decade to an installed capacity of more than 2000 MW, in various parts of the world and the transmission voltage has increased to ± 533 KV. There are now about 23 projects in operation or under construction throughout the world.

The rapid development of semiconductor technology has revolutionised the art of power modulation. Thyristor valve is an important component of HVDC system and is used in the schemes that are commissioned after 1970 and has replaced the mercury arc valves that were in the previous existing schemes. The use of better converter transformers, harmonic filters and the powerful control schemes has improved the performance of the HVDC systems to a greater extent. The development of HVDC circuit breakers and the introduction of multiterminal systems would further revolutionise the use of DC links in future.

1.2 MERITS AND DEMERITS OF HVDC TRANSMISSION

HVDC transmission technology has developed due to its recognised significant economic and technical advantages for certain specific power system transmission and interconnection applications. To appreciate this new concept, one should make a comparative study of AC and DC transmission. A brief comparative study, bringing out the importance of DC transmission is presented here in the following text.

For the same amount of power to be transmitted, a bipolar (having two conductors) DC scheme is cheaper than the single circuit three-phase AC scheme of similar conductor dimensions and clearances. Hence greater power per conductor can be transmitted in the case of DC schemes.

In the case of bipolar DC scheme, the loss of one conductor results in a 50% loss of transmitting capacity compared to a complete shut down of transmission in the case of a single circuit three phase AC line, thus DC transmission is more reliable.

Due to the absence of charging effect, DC cables have no limitations on length as against the AC cables.

It is well known that AC system stability is dependent on the power per circuit and the length of the line. For long lines it thus leads to the introduction of stabilising equipment (series capacitors etc.) which obviously increase the system cost. In the case of DC, no such

stabilising equipment is needed as DC line length has no relation to the stability of the system. Moreover, it was proved that in the AC/DC systems, the stability of the associated AC system can be greatly improved through the DC power modulation.

The short circuit level in AC systems may sometime demand the upgrading of existing AC circuit breakers where as in DC links, the short circuit currents can be limited with the help of current controllers.

The DC link can be used in interconnecting systems of different frequencies. Absence of skin effect, less corona loss and radio interference, and usage of earth as a return conductor are also some of the advantages of DC systems.

However DC transmission has some disadvantages which can be summarised as follows.

The converters in the DC system generate harmonics and thus arising the need for filter circuits. Converters are expensive and in addition, filters increase the overall cost of the system.

Eventhough the DC line itself does not require any reactive power compensation, the converters require much reactive power and must be supplied locally.

Due to lack of HVDC circuit breakers, the tapping of DC line is not yet possible and hence the use is limited in point to point transmission.

It is quite clear from the above discussion that the line costs are higher for AC and terminal costs are higher for DC. So if the line is long enough to give sufficient savings in line costs to off-set the higher terminal costs, DC provides a more economical solution.

1.3 REVIEW OF SIMULATION STUDIES

Simulation studies are necessary in the planning and design stages and in the study of operation of DC links. HVDC simulators are used for all these purposes and some of the problems that can be simulated with the help of a HVDC simulator are as follows:

1. The development of concepts and equipment for control and protection of HVDC system. This includes:

a) Control of power, current and extinction angle in two terminal and multiterminal systems.

b) The effects of AC and DC line faults on the control performance.

c) Determination of overcurrent and overvoltage stresses in various components of the system.

2. Analysis of various phenomena in DC as well AC/DC systems, which includes:

a) HVDC operation with weak AC systems.

b) Stability and damping introduced by HVDC systems.

c) Control methods for influencing the reactive power characteristics of AC systems.

d) Smoothing of harmonics through filters and reduction of noncharacteristic harmonics.

So far HVDC simulator is the most versatile tool available for simulation studies although digital simulation is also being considered for specific problems because of its flexibility. A model suffers from the difficulty that costs increase as it becomes sufficiently versatile to represent a wide range of system configurations and also scaling of components may produce difficulties. The disadvantage of the digital simulation for HVDC systems is the complexity required in a detailed simulation, where each component of the system has to be modelled accurately. The attendant problem of increased computer time and storage has so far necessitated in use of different levels of detail in the modelling of the system. For example, an analysis of dynamic stability of the AC/DC system would require only a simplified model of the DC link. But for the transient analysis and for accurate simulation of the high frequency effects a detailed simulation of the converter is essential.

Digital Simulation of Converters: Any system can be simulated on digital computer, if the dynamic performance of the system can be represented by a set of equations, may be algebraic, differential or boolean. Digital simulation of bridge converters began to be dealt with about fifteen years ago. All the simulation methods so far considered can be classified into two groups.

The first category of simulation methods[7,8] use a transformation technique, by which the state equations corresponding to each of the state of the converter are formed and solved. The transformation matrix is automatically computed by the computer.

In the second category[5,6,11], the programs contain all the state equations of the possible circuits corresponding to the conducting sets of thyristors and at every instant the program selects the proper set of equations for solution. In ref.5, the authors have suggested a method called central process method, in which the central process starts from the instant of firing a valve to the instant of next firing. The central processes are mathematically represented by a set of differential and boolean equations. Depending upon the state of the converter, the differential equations, phase to phase voltages are selected and solved. Later the work is extended[6] to simulate the HVDC transmission system under abnormal conditions. The central process method seems to be rather complicated when compared to the method suggested by Htsui and Shepherd[11]. In this simulation work, generalized differential equations are formulated after deriving the differential equations corresponding to all possible normal combinations of conducting valves.

1.4 SUMMARY OF THE THESIS

In this thesis the problem of converter simulation is examined with a fresh view point of trying to determine the general structure of the system equations for all possible modes of operation of the converter including normal and abnormal ones. In all, there are 47 possible modes with a) two b) three c) four valves conduction. It is shown that the system equations for all these modes can be derived from a basic set of equations derived from topological considerations. Thus the problem of converter simulation is put in the general framework of the problem of analysis of a network with controlled switches. The existence of the solution to this general problem is also revealed by examination of the basic equations.

The approach adopted in this thesis is to develop sets of generalized differential equations, each set corresponding to a certain category of the possible modes. This approach is along the lines given in ref.11. However, the development of these generalized set of equations proceeds from the basic equations derived from the network topology.

A computer program for digital simulation of converters in a HVDC link is developed incorporating the features mentioned above. This is applied for the transient analysis of the converters under both normal and abnormal operating conditions, where the direct current is continuous. There are 39 possible modes for this condition.

The chapterwise description of the thesis is given below:

i. The second chapter deals with the mathematical representation of the three phase bridge converter and the generalized equations are developed for both normal and abnormal operating conditions. The generalized equations are presented in a form, that can be easily implemented on a digital computer.

ii. The computer flow chart is included in the third chapter and it describes the programming techniques to apply the mathematical model developed in Chapter 2, for efficient computer simulation. The program is utilized in this chapter for the transient analysis of a 3-phase bridge converter.

iii. The fourth chapter presents the application of the computer program for the analysis of abnormal operating conditions in a two terminal HVDC system consisting of six pulse converters at the rectifier and inverter stations. Two types of faults are considered - (i) drop in the inverter voltage leading to commutation failure and (ii) misoperation of the inverter valves. The results of the study are presented and compare favourably with those given in the previous literature.

This chapter also presents the development of a simple procedure for the simulation of converter controls at the rectifier. The results with and without the controller are compared.

CHAPTER 2

MATHEMATICAL MODELLING OF A CONVERTER

2.1 INTRODUCTION

The varying topology of a converter caused by the commencement and cessation of valve conduction makes dynamic simulation extremely difficult. To simulate dynamic operation, the system must be presented in a form acceptable for computer solution. Hence to represent the complete system in detail by a mathematical model, the equations corresponding to all possible circuits formed, depending on the conducting states of various valves, are considered and the generalised equations are formulated. These equations are presented in a form that can be easily implemented on a digital computer.

2.2 FORMULATION OF EQUATIONS

The three phase bridge converter is shown in Fig.2.1.a in which the valves are numbered in their firing sequence. L_d is the smoothing reactor and R_d is its resistance. Fig.2.1.b is the network corresponding to the AC power source connected to nodes 2, 3 and 4. R's and L's are the source resistances and inductances respectively. The formulation of equations is based on the graph shown in Fig.2.1.c. Here the circuit of Fig.2.1.b is represented by two branches (7 and 9), utilizing the multiterminal representation for networks.

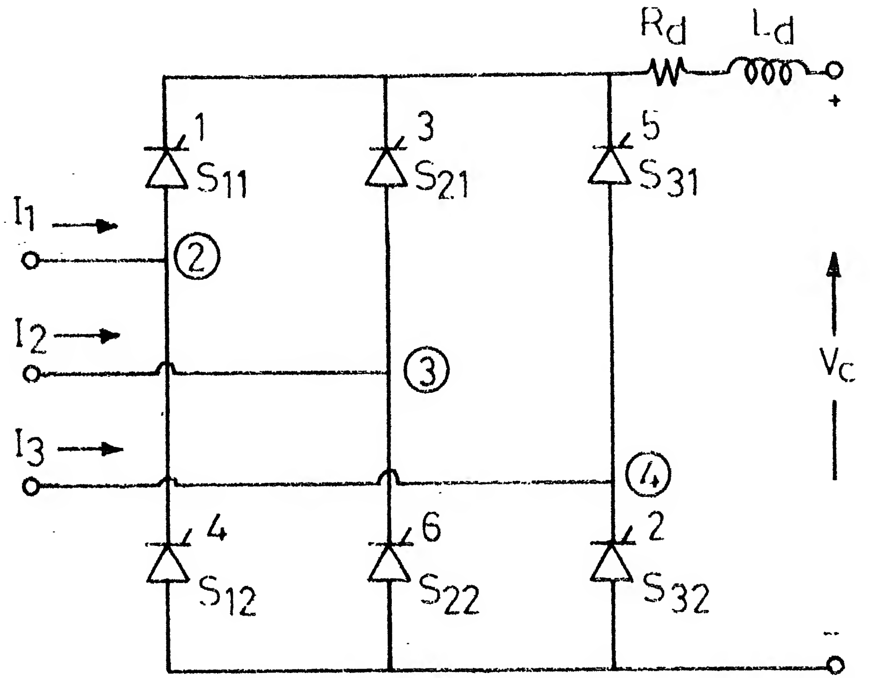

Fig. 2.1.a

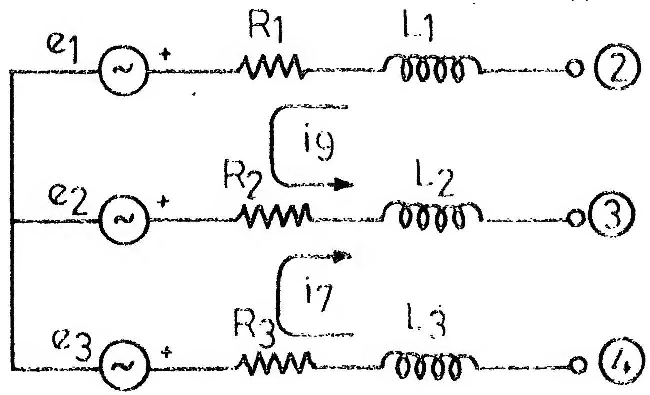

Fig. 2.1.b

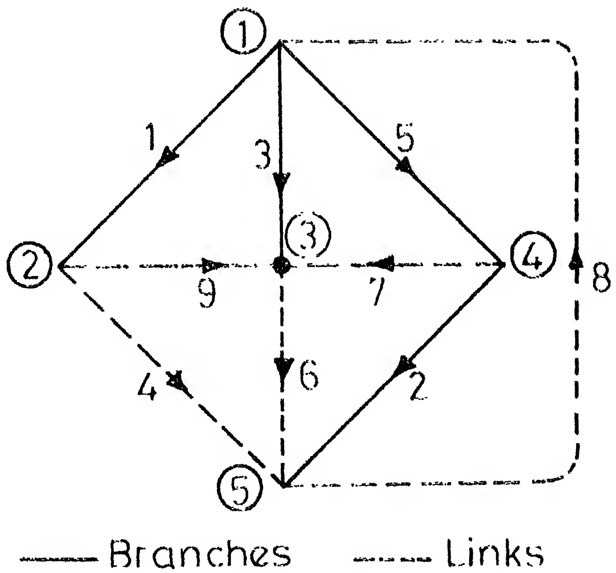

Fig. 2.1.c

Fig. 2.1 - Bridge converter and the associated graph

In the formulation of equations valves are treated as ideal switches having no forward resistance and infinite reverse resistance. The following equations can be easily derived from Figs. 2.1.b and 2.1.c.

$$\begin{bmatrix} V_{L7} \\ V_{L8} \\ V_{L9} \end{bmatrix} = \begin{bmatrix} (L_3+L_2)p+(R_2+R_3) & 0 & (L_2p + R_2) \\ 0 & (R_d+L_dp) & 0 \\ (L_2p+R_2) & 0 & (L_1+L_2)p+(R_1+R_2) \end{bmatrix} \begin{bmatrix} i_7 \\ i_8 \\ i_9 \end{bmatrix}$$

$$+ \begin{bmatrix} e_3-e_2 \\ -V_c \\ e_1-e_2 \end{bmatrix} \qquad (2.1)$$

The relation between the branch currents and the link currents can be expressed in the following form:

$$\begin{bmatrix} 0 & 0 & 1 & -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 & 0 & -1 & -1 \\ -1 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 & 0 & -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} i_7 \\ i_8 \\ i_9 \\ i_1 \\ i_2 \\ i_3 \\ i_5 \\ i_4 \\ i_6 \end{bmatrix} = 0$$

The above equation can be expressed in a simple form

$$A\, i = 0 \qquad (2.2)$$

The tree branch voltages and the link voltages can be related as in equation (2.3).

$$\begin{bmatrix} V_4 \\ V_6 \\ V_7 \\ V_8 \\ V_9 \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 & 1 \\ 0 & 1 & -1 & 1 \\ 0 & 0 & 1 & -1 \\ 0 & -1 & 0 & -1 \\ -1 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_5 \end{bmatrix} \tag{2.3}$$

Combining equations (2.1) and (2.3), we get

$$\begin{bmatrix} Z & K_1 \\ 0 & K_2 \end{bmatrix} \begin{bmatrix} i_L \\ V \end{bmatrix} = \begin{bmatrix} e \\ 0 \end{bmatrix} \tag{2.4}$$

where the submatrices are defined as follows:

$$Z = \begin{bmatrix} (L_3+L_2)p+(R_2+R_3) & 0 & (L_2p+R_2) \\ 0 & (L_d p+R_d) & 0 \\ (L_2p + R_2) & 0 & (L_1+L_2)p+(R_1+R_2) \end{bmatrix}$$

$$K_1 = \begin{bmatrix} 0 & 0 & -1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 1 & -1 & 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 & -1 & 1 \end{bmatrix}$$

$$i_L = \begin{bmatrix} i_7 \\ i_8 \\ i_9 \end{bmatrix}; \quad V = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix}; \quad e = \begin{bmatrix} (e_2-e_3) \\ V_c \\ (e_2-e_1) \end{bmatrix}$$

The equations (2.2) and (2.4) are the basic equations from which the state equations for a given mode can be obtained. In equation (2.2) the valve currents corresponding to the non-conducting valves are set equal to zero and the equation can be rewritten as

$$A_R\ i_R = 0 \tag{2.5}$$

where A_R is the reduced matrix obtained from A by eliminating the columns corresponding to the nonconducting valves. i_R is the reduced current vector.

Depending upon the number of conducting valves, three cases can be considered:

(a) Two valves conduction: In this case the two valve currents and two of the inductor currents can be solved in terms of the remaining inductor current, say i_8.

(b) Three valves conduction: In this case the three valve currents and one of the inductor currents can be solved in terms of the remaining two inductor currents.

(c) Four valves conduction: In this case all the four valve currents can be expressed in terms of all the three inductor currents.

From the solution of equation (2.5), one can write

$$i_L = T\ u \tag{2.6}$$

where T is the suitable transformation matrix and u is the vector of independent inductor currents.

Equation (2.4) is reduced by putting the voltages corresponding to the conducting valves to zero. By deleting the columns corresponding to the conducting valves, the matrices K_1 and K_2 are reduced and the equation (2.4) can be reduced to the following form:

$$\begin{bmatrix} Z & K_3 \\ 0 & K_4 \end{bmatrix} \begin{bmatrix} i_L \\ V_R \end{bmatrix} = \begin{bmatrix} e \\ 0 \end{bmatrix} \qquad (2.7)$$

In the above equation V_R is the reduced vector formed from V after substituting zeros for conducting valve voltages.

After substituting for i_L in equation (2.7), we finally get

$$\begin{bmatrix} ZT & K_3 \\ 0 & K_4 \end{bmatrix} \begin{bmatrix} u \\ V_R \end{bmatrix} = \begin{bmatrix} e \\ 0 \end{bmatrix} \qquad (2.8)$$

It is to be noted that the sum of the dimensions of the vector u and V_R is equal to five and we get five equations in five unknowns which have to be solved. Actually what is required is, the derivation of the differential equations in u by eliminating the valve voltages and algebraic expressions for valve voltages in terms of the right hand side quantities of equation (2.8), which are known.

The above procedure is explained in next section by considering some normal and abnormal modes of converter operation.

2.3 EXAMPLES

Ex. 1: A normal mode is considered and let the conducting valves are 1 and 2. Let i_8 be the known current from the previous state of the converter. So

$$\bar{u} = i_8 \tag{2.9.a}$$

As valves 1 and 2 are conducting we can substitute $i_3 = i_4 = i_5 = i_6 = 0$ in equation (2.2) and $V_1 = V_2 = 0$ in equation (2.4).

From equation (2.5), we can obtain

$$i_1 = i_9 \quad ; \quad i_2 = i_8 \tag{2.9.b}$$

and also

$$\bar{i}_L = \begin{bmatrix} -1 \\ 1 \\ 1 \end{bmatrix} \bar{u} \tag{2.9.c}$$

Substituting equation (2.9.c) in equation (2.4), we get

$$\begin{bmatrix} -(L_3p+R_3) & -1 & 0 & 1 & 0 \\ (L_dp+R_d) & 0 & 0 & 1 & 0 \\ (L_1p+R_1) & -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_8 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} \\ e \\ \\ 0 \\ \\ \end{bmatrix} \tag{2.10}$$

From the above equation the expressions for unknown vectors can be formulated.

$$pi_8 = \frac{1}{L_1+L_3+L_d} [(e_3+V_c-e_1) - (R_1+R_3+R_d)\, i_8]$$

$$V_3 = \left(\frac{L_d + L_3}{L_1+L_3+L_d} \right) e_1 - e_2 + \left(\frac{L_1}{L_1+L_3+L_d}\right)(e_3+V_c)$$
$$+ [R_1 - \left(\frac{L_1}{L_1+L_3+L_d}\right)(R_1+R_3+R_d)]\, i_8$$

$$V_5 = \left(\frac{L_d}{L_1+L_3+L_d}\right)(e_1-e_3) + \left(\frac{L_1+L_3}{L_1+L_3+L_d}\right)V_c$$
$$- [R_d - \left(\frac{L_d}{L_1+L_3+L_d}\right)(R_1+R_3+R_d)]\, i_8$$

$$V_4 = V_5$$
$$V_6 = V_5 - V_3.$$

Ex. 2: Let the conducting valves be 1, 2 and 3 and let the currents i_8 and i_9 are known.

From equation (2.5),

$$i_1 = i_9$$
$$i_2 = i_8$$
$$i_3 = i_8 - i_9$$

From equation (2.5), T can be found out and substituting in equation (2.6)

$$i_L = \begin{bmatrix} -1 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_8 \\ i_9 \end{bmatrix} \qquad (2.11)$$

Substituting equation (2.11) and the known voltages in equation (2.4), we get

$$\begin{bmatrix} -\{(L_3+L_2)p+(R_3+R_2)\} & (L_2p+R_2) & 0 & 1 & 0 \\ (L_dp+R_d) & 0 & 0 & 1 & 0 \\ -(L_2p+R_2) & (L_1+L_2)p+(R_1+R_2) & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & -1 & 1 \end{bmatrix} \begin{bmatrix} i_8 \\ i_9 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} \\ e \\ \\ 0 \\ \end{bmatrix} \tag{2.12}$$

From equation (2.12) the unknown vector can be solved and the expressions are as follows:

$$pi_8 = \frac{1}{D}[\{(e_3+V_c)(L_1+L_2)-(e_2L_1+e_1L_2)\} - \{(R_3+R_d)(L_1+L_2)+R_2L_1\}i_8$$
$$-(R_1L_2-R_2L_1)i_9] .$$

$$pi_9 = \frac{1}{D}[\{(e_2-e_1)(L_3+L_d)+(e_3-e_1+V_c)L_2\} - \{(R_3+R_d)L_2-R_2(L_3+L_d)\}i_8$$
$$- \{(R_1+R_2)(L_3+L_d) + R_1L_2\}i_9] .$$

$$V_5 = \frac{D_1}{D}V_c + \frac{L_d}{D}[\{(e_1L_2+e_2L_1)-e_3(L_1+L_2)\} + \{(R_3+R_d)(L_1+L_2)$$
$$+ R_2L_1 - \frac{R_d}{L_d}D\}i_8 + (R_1L_2-R_2L_1)i_9] .$$

$$V_4 = V_6 = V_5$$

where $D_1 = L_1L_2 + L_2L_3 + L_3L_1$

and $D = D_1 + L_d(L_1+L_2)$.

The above two examples refer to the normal operation of converter, in which valve currents are same as the phase currents. The following three examples refer to the abnormal operation of converter.

Ex.3: Let the conducting valves be 1 and 4 and i_8 be the known current.

We can substitute

$$i_2 = i_3 = i_5 = i_6 = 0 \quad \text{in equation (2.2)}$$

and $$V_1 = V_4 = 0 \quad \text{in equation (2.4).}$$

From equations (2.2) and (2.6)

$$i_L = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} i_8 \tag{2.13}$$

Substituting this in equation (2.4),

$$\begin{bmatrix} 0 & 0 & -1 & 1 & 0 \\ (R_d+L_dp) & 1 & 0 & 1 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & -1 & 0 & -1 & 0 \\ 0 & -1 & 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} i_8 \\ V_2 \\ V_3 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} \\ e \\ \\ 0 \\ \\ \end{bmatrix} \tag{2.14}$$

From equation (2.14), we get

$$pi_8 = \frac{1}{L_d}(V_c - R_d\, i_8)$$

$$V_3 = (e_1 - e_2)$$

$V_5 = (e_1 - e_3)$

$V_6 = -V_3$

$V_2 = -V_5$

In this case, it can be noted that there is a short circuit on the dc link and all the three phases are open circuited. So the currents through the conducting valves are same as the dc link current i.e., i_8.

Ex.4: Let the conducting valves are 1, 4 and 3. Let i_8 and i_9 be known.

We can substitute

$$V_1 = V_4 = V_3 = 0$$

$$i_2 = i_5 = i_6 = 0$$

and $$u = \begin{bmatrix} i_8 \\ i_9 \end{bmatrix}$$

From equation (2.2)

$$T = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{2.15}$$

and also

$$i_1 = i_9 + i_8$$

$$i_4 = i_8$$

$$i_3 = -i_9$$

From equation (2.7)

$$\begin{bmatrix} 0 & (L_2p+R_2) & 0 & 1 & 0 \\ (L_dp+R_d) & 0 & 1 & 1 & 0 \\ 0 & (L_1+L_2)p+(R_1+R_2) & 0 & 0 & 0 \\ 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} i_8 \\ i_9 \\ V_2 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} \\ e \\ \\ 0 \\ \\ \end{bmatrix} \qquad (2.16)$$

From equation (2.16), it can be written as

$$pi_8 = \frac{1}{L_d}(V_c - R_d i_8)$$

$$pi_9 = \frac{1}{L_1+L_2}[(e_2-e_1)-(R_1+R_2)i_9]$$

$$V_5 = \frac{1}{L_1+L_2}[(e_2L_1+e_1L_2) - e_3(L_1+L_2) + i_9(R_1L_2-R_2L_1)]$$

$$V_2 = -V_5$$

$$V_6 = 0$$

In this case there is a short circuit on phases 1 and 2 and also on dc link.

<u>Ex.5</u>: Let the conducting valves are 1,2,3 and 4 and let i_L is known.

So $V_1 = V_2 = V_3 = V_4 = 0$; $i_5 = i_6 = 0$

and T is a unit matrix.

From equation (2.5) the valve currents can be obtained as

$$
\begin{aligned}
i_1 &= i_7 + i_8 + i_9 \\
i_2 &= -i_7 \\
i_3 &= -(i_7+i_9) \\
i_4 &= (i_7+i_8)
\end{aligned}
\qquad (2.17)
$$

From equation (2.4)

$$
\left[\begin{array}{ccc|cc}
 & & & 1 & 0 \\
 & Z & & 1 & 0 \\
 & & & 0 & 0 \\
\hline
 & 0 & & -1 & 0 \\
 & & & -1 & 1
\end{array}\right]
\begin{bmatrix} i_7 \\ i_8 \\ i_9 \\ V_5 \\ V_6 \end{bmatrix}
=
\begin{bmatrix} \\ e \\ \\ 0 \\ \\ \end{bmatrix}
\qquad (2.18)
$$

From equation (2.18) the following expressions can be derived:

$$
pi_7 = \frac{1}{D_1} [\{(e_1L_2+e_2L_1) - e_3(L_1+L_2)\} - \{ R_3(L_1+L_2)+R_2L_1 \} i_7 + (R_1L_2-R_2L_1)i_9]
$$

$$
pi_8 = \frac{1}{L_d}(V_c - R_d i_8)
$$

$$
pi_9 = \frac{1}{D_1} [\{(e_3L_2+e_2L_3) - e_1(L_2+L_3)\} + (R_3L_2-R_2L_3)i_7 - \{R_1(L_2+L_3)+R_2L_3\} i_9]
$$

$$
V_5 = V_6 = 0
$$

where $D_1 = L_1L_2 + L_2L_3 + L_3L_1$.

It can be noted that, in this case, the three phases are short circuited and also the dc link.

2.4 CLASSIFICATION OF MODES

In the normal operation of a three phase bridge converter, either two valves or three valves are conducting simultaneously. Therefore there will be 12 different modes of operation per cycle. In the abnormal operation, there are 27 possible abnormal modes assuming that the DC link is not open circuited and all these are considered in the present simulation. In the above five examples five different modes are explained and in fact all these existing modes whether normal or abnormal can be divided into three groups as shown in Table 2.1.

GROUPS	NORMAL MODES	ABNORMAL MODES	TOTAL
2 Valves conduction	(1,2) (2,3) (3,4) (4,5) (5,6) (6,1)	(1,4) (3,6) (5,2)	9
3 Valves conduction	(1,2,3) (2,3,4) (3,4,5) (4,5,6) (5,6,1) (6,1,2)	(1,4,3) (1,4,6) (1,4,5) (1,4,2) (3,6,1) (3,6,4) (3,6,2) (3,6,5) (5,2,1) (5,2,4) (5,2,3) (5,2,6)	18
4 Valves conduction		(1,2,3,4) (2,3,4,5) (3,4,5,6) (4,5,6,1) (5,6,1,2) (6,1,2,3) (1,3,5,4) (1,3,5,6) (1,3,5,2) (2,4,6,1) (2,4,6,3) (2,4,6,5)	12

Table 2.1: Classification of Modes.

The generalised equations for the 5 different sets of modes are given in the subsequent section in the form that can be easily implemented on a digital computer.

2.5 GENERALIZED EQUATIONS

2.5.1 General Definitions: The following points are to be noted in connection with the symbols used in the equations.

i) Each valve of Fig.2.1.a is represented by S_{lm} in which the first suffix l, indicates the phase number (1,2, or 3) to which the valve is connected and the second suffix m indicates whether the valve belongs to upper group or lower group. It is to be noted that valves 1,3 and 5 belong to upper group and the lower group is formed by valves 2,6 and 4. So m can take values 1 or 2 in which 1 corresponds to upper group.

ii) Valve switching logic: $S_{lm} = 1$ if the valve is conducting

$= 0$ if the valve is not conducting.

iii) All the lower case letters are suffixes except p and e. Suffixes except d and c will be defined as per the mode.

P is a suffix, but p indicates the derivative (d/dt)

d is used in connection with smoothing reactor (L_d) and its resistance (R_d) and c with dc voltage (V_c).

e is the sinusoidal phase voltage.

I indicates the current.

iv) In the formulation of generalized equations for the abnormal cases, the equations for valve currents are to be formulated, for which we need the conducting valve numbers. For this purpose valve numbers can be obtained from the matrix N of order 3x2.

$$N = \begin{bmatrix} 1 & 4 \\ 3 & 6 \\ 5 & 2 \end{bmatrix}$$

Valve numbers are indicated by n1, n2, n3 etc., and the above matrix elements by N_{11}, N_{12}, N_{21}, etc.,

v) V(l,m) is used to indicate the voltage across a valve, where l and m are as defined in (i).

2.5.2 Two Valves Conduction (Normal Mode):

i. Note i and j for which $S_{i1} = S_{j2} = 1$; Define $p=6-(i+j)$.

ii. $$pI_8 = \frac{1}{(L_i+L_j+L_d)}[(e_j-e_i+V_c) - (R_i+R_j+R_d)I_8]$$

iii. Phase currents: $I_i = -I_8$; $I_j = I_8$; $I_p = 0$.

iv. $V(i,1) = V(j,2) = 0$.

v. $$V(j,1) = \frac{L_d}{L_i+L_j+L_d}(e_i-e_j) + \left(\frac{L_i+L_j}{L_i+L_j+L_d}\right)V_c - \left[R_d - \left(\frac{L_d}{L_i+L_j+L_d}\right)(R_i+R_j+R_d)\right] I_8.$$

vi. If j=2 set a=2; b=1; D=E=F = -1 and interchange i and j for this step only.

If $j \neq 2$ set $a = 1$; $b = 2$; $D = E = F = 1$

$$V(P,a) = \left(\frac{L_d+L_j}{L_i+L_j+L_d}\right)^D e_i - E\, e_P + \left(\frac{L_i}{L_i+L_j+L_d}\right)(F\, e_j+V_c)$$

$$+ \left[R_i + \frac{(R_i+R_j+R_d)}{(L_i+L_j+L_d)} L_i\right] I_8.$$

vii. $V(i,2) = V(j,1)$

$$V(P,b) = V(j,1) - V(P,a).$$

2.5.3 Three Valves Conduction (Normal Mode):

i. Note i,j and P for which $S_{i1} = S_{j1} = S_{P2} = 1$ and set $q=1$

or

Note i,j and P for which $S_{i2}=S_{j2} = S_{P1} = 1$ and set $q=-1$.

In the above step, select i and j such that $i < j$.

ii. If $i = 2$ set $k = i$; $l = j$; $s = 7$; $u = 9$

Otherwise set $k = j$; $l = i$; $s = 9$; $u = 7$.

iii. $C = L_1L_2 + L_2L_3 + L_3L_1$ and $D = C + L_d(L_i+L_j)$

$$pI_8 = \frac{1}{D}\left[\{(qe_P+V_c)(L_i+L_j)-q(e_jL_i+e_iL_j)\}\right.$$

$$\left. - \{(R_P+R_d)(L_i+L_j) + R_kL_l\} I_8 - q(R_lL_k-R_kL_l)I_s\right]$$

$$pI_s = \frac{1}{D}\left[\{(e_k-e_l)(L_P+L_d)+(e_P-e_l+qV_c)L_k\}\right.$$

$$\left. - q\{(R_P+R_d)L_k-R_k(L_P+L_d)\} I_8 - \{(R_i+R_j)(L_P+L_d)+R_lL_k\} I_s\right]$$

iv. Set $B = 1$ if $P = 2$

$= 0$ otherwise.

Set $A = -1$ if $S_{21} = 1$

$= 1$ otherwise.

$I_u = A\,I_8 - B\,I_s$

Set $x = 3$, $y = 1$, if $P = 1$

$x = 1$, $y = 3$ otherwise.

$\bar{I}_x = -\bar{I}_s$; $\bar{I}_y = -\bar{I}_u$ and $\bar{I}_2 = -(\bar{I}_x + \bar{I}_y)$.

v. If $q = 1$ set $V(i,1) = V(j,1) = V(P,\ 2) = 0$ and

$g = 2$; $h = 1$.

If $q = -1$ set $V(i,2) = V(j,2) = V(P,1) = 0$ and

$g = 1$; $h = 2$.

$$V(i,g) = \frac{C\,V_c}{D} - \frac{L_d}{D}\Big[\ \{q e_P(L_i+L_j) - q(e_j L_i + e_i L_j)\}$$

$$-\{(R_P+R_d)(L_i+L_j)+R_k L_l - \frac{R_d}{L_d}D\}\ I_8$$

$$-\ q(R_l L_k - R_k L_l) I_s\ \Big]$$

$V(j,g) = V(i,g) = V(P,h)$.

2.5.4 Two Valves Conduction (Abnormal Mode):

Let n1 and n2 are the conducting valves.

i. Note i for which $S_{i1} = 1$

$j = i+1$ if $i \neq 3$

$= 1$ if $i = 3$

$P = 6 - (i+j)$.

ii. $pI_8 = \frac{1}{L_d}(V_c + R_d I_8)$

$I_1 = I_2 = I_3 = 0$ (All the phase currents are zero).

iii. $V(i,1) = V(i,2) = 0$

$V(j,1) = \bar{e}_i - \bar{e}_j$

$V(j,2) = -V(j,1)$

$V(P,1) = \bar{e}_i - \bar{e}_P$

$V(P,2) = -V(P,1)$.

iv. Valve currents: $I_{n1} = I_8 = I_{n2}$.

2.5.5 Three Valves Conduction (Abnormal Mode):

i. Note i,j and P for which $S_{i1} = S_{j1} = S_{P2} = 1$ and set q=1

or

Note i, j and P for which $S_{i2} = S_{j2} = S_{P1} = 1$ and set q=-1.

In the above, select i and j such that i < j.

ii. If $i = 2$ set $s = 7$, $M = -1$, $x = 1$, $y = 3$

otherwise $s = 9$, $M = 1$, $x = 3$, $y = 1$.

iii. $pI_8 = \frac{1}{L_d}(V_c - R_d\, I_8)$

$$pI_s = \frac{1}{L_i + L_j}[M(e_j - e_i) - (R_i + R_j)I_s]$$

iv. Set $A = 0$ if $i = 2$ or $j = 2$

$= 1$ otherwise

$I_x = A\, I_s$

$I_y = -I_s$

$I_2 = -(I_x + I_y)$.

v. Valve currents:

If $q = 1$ set $n1 = N_{i1}$, $n2 = N_{j1}$, $n3 = N_{P2}$

or

If $q = -1$ set $n1 = N_{i2}$, $n2 = N_{j2}$, $n3 = N_{P1}$

Set $R = 1$ if $i = P$

$= 0$ otherwise.

$I_{n1} = R\, I_8 + q\, I_j$

$I_{n2} = I_8 - I_{n1}$

$I_{n3} = I_8$.

vi. If $q = 1$ set $V(i,1) = V(j,1) = V(P,2) = 0$

otherwise set $V(i,2) = V(j,2) = V(P,1) = 0$

If $q = 1$ and $i = P$ set $V(j,2) = 0$ otherwise $V(i,2) = 0$.

If $q = -1$ and $i = P$ set $V(j,1) = 0$ otherwise $V(i,1) = 0$.

$$V(P,2) = \frac{1}{L_i+L_j}[\{e_P(L_i+L_j)-(e_iL_j+e_jL_i)\} - M(R_iL_j-R_jL_i)I_s]$$

$$V(P,1) = -V(P,2).$$

2.5.6 Four Valves Conduction:

i. $$pI_8 = \frac{1}{L_d}(V_c - R_dI_8)$$

$$pI_9 = \frac{1}{D_1}[\{(e_3L_2+e_2L_3)-e_1(L_2+L_3)\} + (R_3L_2-R_2L_3)I_7$$

$$- \{R_1(L_2+L_3)+R_2L_3\}I_9]$$

$$pI_7 = \frac{1}{D_1}[\{(e_1L_2+e_2L_1)-e_3(L_1+L_2)\} - \{R_3(L_1+L_2)+R_2L_1\}I_7$$

$$+ (R_1L_2 - R_2L_1)I_9]$$

where $D_1 = L_1L_2+L_2L_3+L_3L_1$.

ii. Phase currents: $I_1 = -I_9$

$I_2 = I_9 + I_7$

$I_3 = -I_7$

Set all the voltages across valves to zero.

iii. Valve currents:

Case (a) $\sum_{l=1}^{3} S_{l1} = \sum_{l=1}^{3} S_{l2} = 2$

Note i,j,k and l for which $S_{i1} = S_{j1} = S_{k2} = S_{l2} = 1$

subject to conditions $i < j$ and $k < l$.

Set $n1 = N_{i1}$, $n2 = N_{j1}$, $n3 = N_{k2}$, $n4 = N_{l2}$.

If $i = k$ or $i = l$ set $A = 1$, $B = -1$, $r = j$.

If $j = k$ or $j = l$ set $A = 0$, $B = 1$, $r = i$.

$I_{n1} = A\, I_8 - B\, I_r$

$I_{n2} = I_8 - I_{n1}$

If $i = k$ or $j = k$ set $M = 1$, $T = 1$, $v = l$.

If $i = l$ or $j = l$ set $M = 0$, $T = -1$, $v = k$.

$I_{n3} = M\, I_8 - T\, I_v$

$I_{n4} = I_8 - I_{n3}$.

Case (b) If $\sum_{l=1}^{3} S_{l1} = 3$ set $n1=N_{11}$, $n2=N_{21}$, $n3=N_{31}$ and note i for which $S_{i2} = 1$ and set $n4=N_{i2}$, $q=-1$

or

If $\sum_{l=1}^{3} S_{l2} = 3$ set $n1 = N_{12}$, $n2 = N_{22}$, $n3 = N_{32}$ and

note i for which $S_{i1} = 1$ and set $n4 = N_{i1}$, $q=1$

Set $a_i=1$ and other a's to zero in the following expressions.

$I_{n1} = qI_1 + a_1 I_d$; $I_{n2} = qI_2 + a_2 I_d$

$I_{n3} = qI_3 + a_3 I_d$; $I_{n4} = I_d$.

2.6 CONCLUSION

In this chapter a detailed representation of three phase bridge converter is considered. Topological approach is used in formulating the generalized equations. All the possible normal and abnormal modes are considered in the formulation. The abnormal cases where the dc link current is discontinuous are not considered.

CHAPTER 3

SIMULATION OF CONVERTER

3.1 INTRODUCTION

This chapter presents the digital simulation of a 3-phase bridge converter based on the mathematical model given in Chapter 2. Computer program is developed that utilizes the generalized equations for a set of modes. Two sets of equations completely describe all the 12 normal modes of operation of a converter.

The program is tested by considering an example of transient analysis of a converter feeding into a dc voltage source.

3.2 DESCRIPTION OF THE COMPUTER PROGRAM

The computer flow diagram for the simulation is given in Fig.3.1, and is described below in detail.

i. Input data: Various input data that are required are mentioned in the flow diagram, in which initial state of the converter corresponds to the numbers of conducting valves at time t and initial values of the phase currents.

ii. Selection of Equations: Under normal operation of converter, two or three valves conduct and depending on the conducting state of the converter valves the equations that are to be solved also change. From the formulation of the

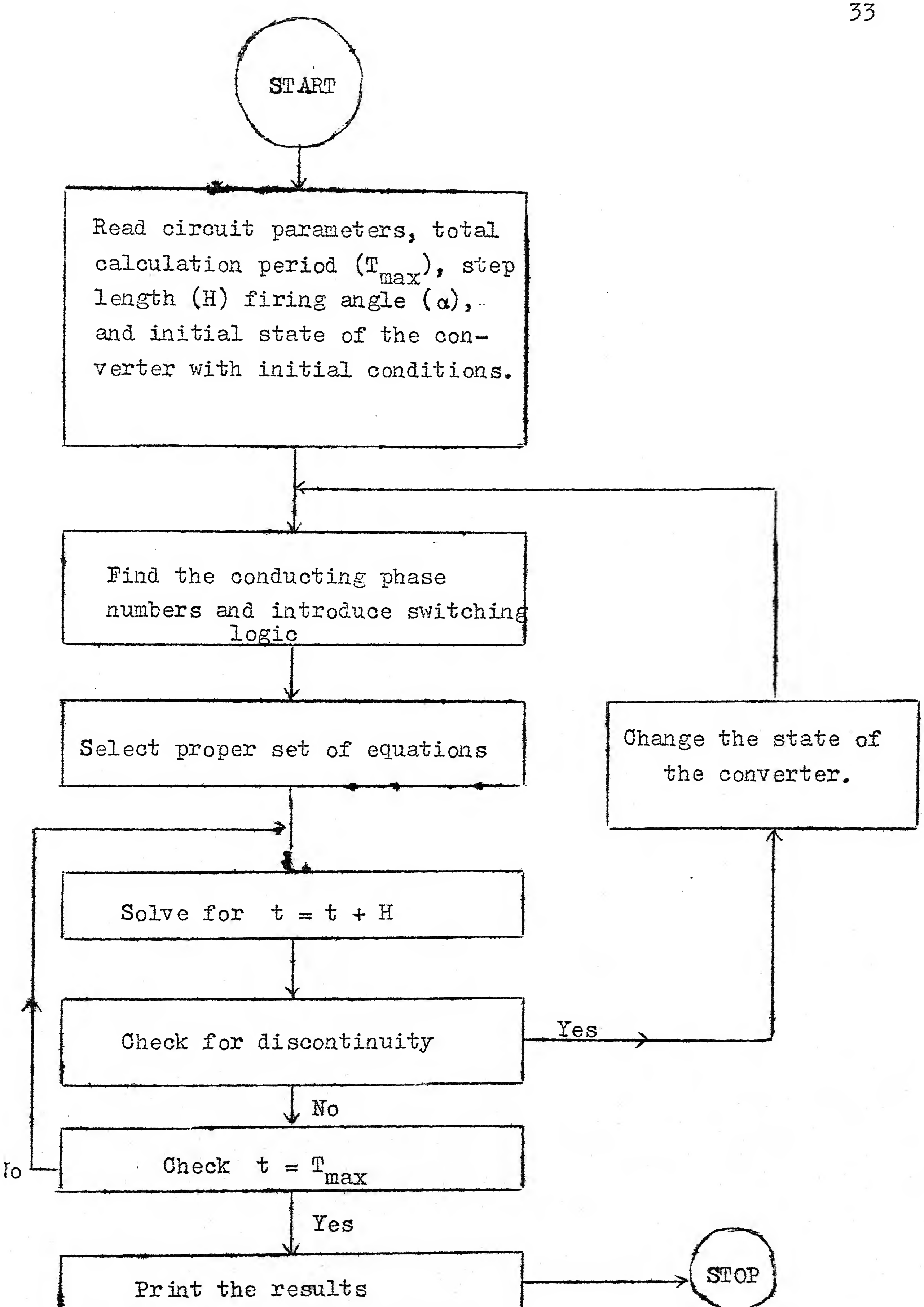

Fig. 3.1 COMPUTER FLOW DIAGRAM.

generalized equations given in previous chapter, the proper set of equations is chosen depending upon the converter modes.

iii. Solution of Selected Equations: The selected differential equations are solved using Runge-Kutta method as it is the most suitable method for the integration of the equations with discontinuities. The accuracy of the solution depends on the size of the step and it should be sufficiently small. In the simulation a step size of 3 electrical degrees is chosen.

iv. Finding the Discontinuity: Discontinuities are created because of two reasons, the commencement and cessation of converter valves.

A valve comes into conducting state only when the voltage across it is greater than a certain voltage and a firing pulse is present. A valve stops conducting when the current through it becomes zero and remains zero for certain time.

Step iii is interrupted if a discontinuity is detected. Having detectcd the presence of discontinuity (as per the conditions mentioned above), it is the next step to find out its exact occurrence during a given step. For this 'linear interpolation' is used as follows.

Let the discontinuity be because of valve cessation i.e., the current through the valve is becoming negative.

Let i_{old} be the current through the outgoing valve at time t_{old} i.e., in the previous step and i_{new} be the present negative current at time t_{new}.

Then by linear interpolation, the exact time $\bar{t}$ at which the current through the outgoing valve becomes zero is

$$\bar{t} = t_{old} + H\, i_{old}/(i_{old} - i_{new}) \qquad (3.1)$$

where H is the integration step size.

The accuracy of this linear interpolation depends on the size of the step length chosen. In similar way, by using eqn.(3.2), all the dependent variables can be interpolated.

$$i_{\bar{t}} = i_{old} + \frac{(\bar{t} - t_{old})}{(t_{old} - t_{new})}(i_{new} - i_{old}) \qquad (3.2)$$

v. Updating the State of Converter: After finding out the variables at the point of discontinuity, the change in the converter state is to be properly implemented for further operation. As already mentioned, the change may be due to an incoming valve or an outgoing valve. Implementation of this change obviously causes a change in the system differential equations and these have to be used to perform the next step of calculation.

3.3 AN EXAMPLE

3.3.1 Description of the System: The example considered here is that of a 3-phase bridge converter feeding into a voltage source as shown in Fig.3.2. It is already assumed (in Chapter 2) that the valves have no forward resistance and infinite reverse resistance and hence in the simulation they are treated as switches which are open during the blocking state and closed during the conducting state.

The system parameters are given below:

Frequency of the ac system	= 50 Hz
AC source line to neutral voltage	= 1.0 p.u.
Reactance of source inductance	= 0.1 p.u.
Source resistance	= 0.0 p.u.
Reactance of smoothing reactor(L_d)	= 0.1 p.u.
Resistance (R_d) of smoothing reactor	= 0.005 p.u.
Value of dc voltage source (V_c)	= 0.65 p.u.
Firing angle (α)	= 60°

All the initial conditions are taken as zero.

3.3.2 Results: The results of the simulation are presented in Figs. 3.3 to 3.6 which show

a) Starting transient of dc link current.

b) Steady state dc link current waveform.

c) Valve voltage waveform in steady state.

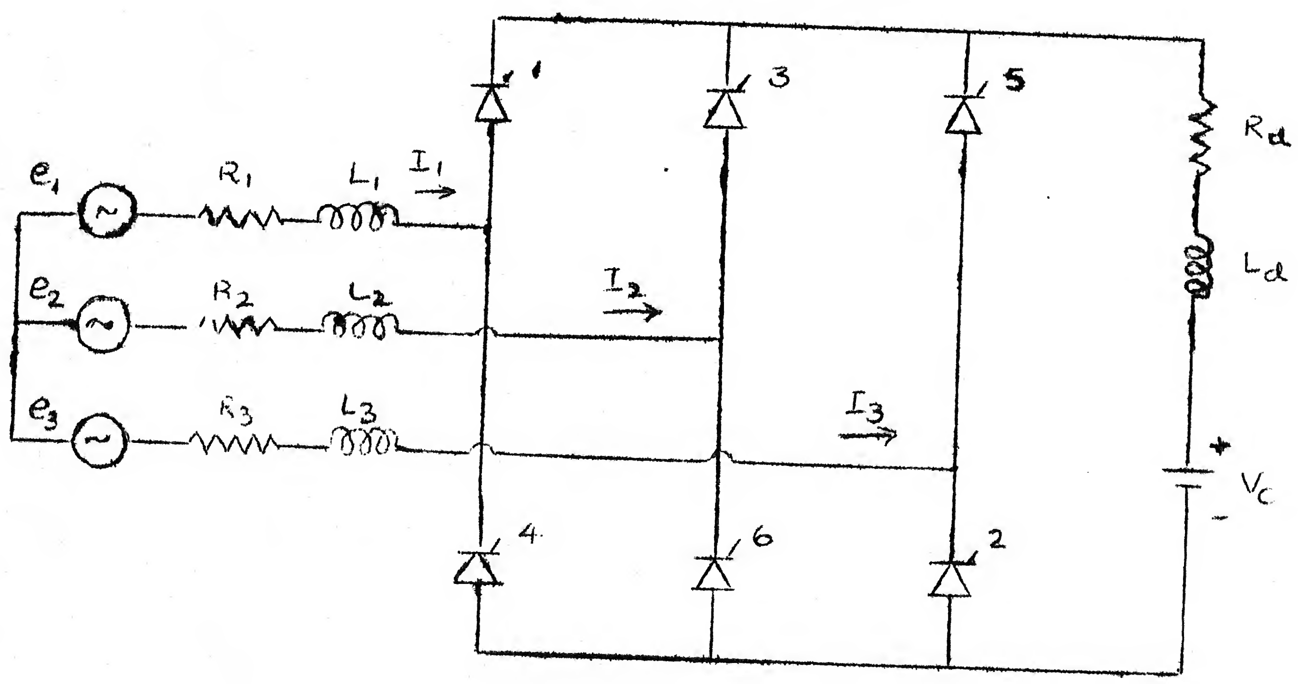

Fig. 3.2. 3 Ø BRIDGE CONVERTER

d) Rectifier terminal voltage waveform in steady state.

e) Steady state valve currents in a cycle.

3.3.3 Discussion: Fig.3.3 shows the variation of direct (average current before and after the steady state is reached. It can be observed from the graph that the current reached steady state in 3 cycles. The average steady state value of the current is 5.38 p.u., whereas the calculated value is 5.175 p.u., by using equation (3.3)

$$V_{dr} = V_{do} \cos\alpha - (\frac{3}{\pi} X_c + R_d) I_d \qquad (3.3)$$

where V_{do} = ideal no load voltage = 2.34 E_{LN}

E_{LN} = AC voltage line to neutral.

α = firing angle.

X_c = commutating reactance = $2\pi f L_s$

L_s = source inductance in henrys

I_d = direct current

V_{dr} = DC source voltage.

From eqn.(3.3),

$$I_d = (V_{do} \cos\alpha - V_{dr})/(\frac{3}{\pi} X_c + R_d)$$

$$= (2.34 \cos 60° - 0.65)/(\frac{3}{\pi} 0.1 + 0.005)$$

$$= \frac{0.52}{0.1005} = 5.175 \text{ p.u.}$$

In the derivation of eqn.(3.3) it is assumed that I_d is a

ripple free direct current. In the present case, the difference between the theoretically calculated value and the computed value is due to the presence of ripple in the direct current. The ripple in the direct current, after allowing the system to reach steady state is observed and is shown in Fig.3.4.

Fig.3.5 shows the variation of the voltage across a valve over one cycle. The instants of extinction and ignition of of valves are also shown. The voltage across valve 1 is indicated with dotted line and the thick line variation is the voltage across valve 1 under ideal conditions. The ideal curve is drawn for the same overlap angle and is compared with the curve obtained from computer values. In this case also the difference observed between the two curves is due to the presence of ripple in the direct current.

Fig.3.6 shows the variation of rectifier terminal voltage and valve currents for a period of one cycle. The valve current curve is not a flat topped one and the variation in valve current can be clearly observed which corresponds to the variations in dc terminal voltage.

The discrepencies in the observed waveforms and the theoretically calculated steady state results are due to the presence of ripple in the direct current. This ripple can be reduced by increasing the value of the smoothing reactor but correspondingly the settling time also increases.

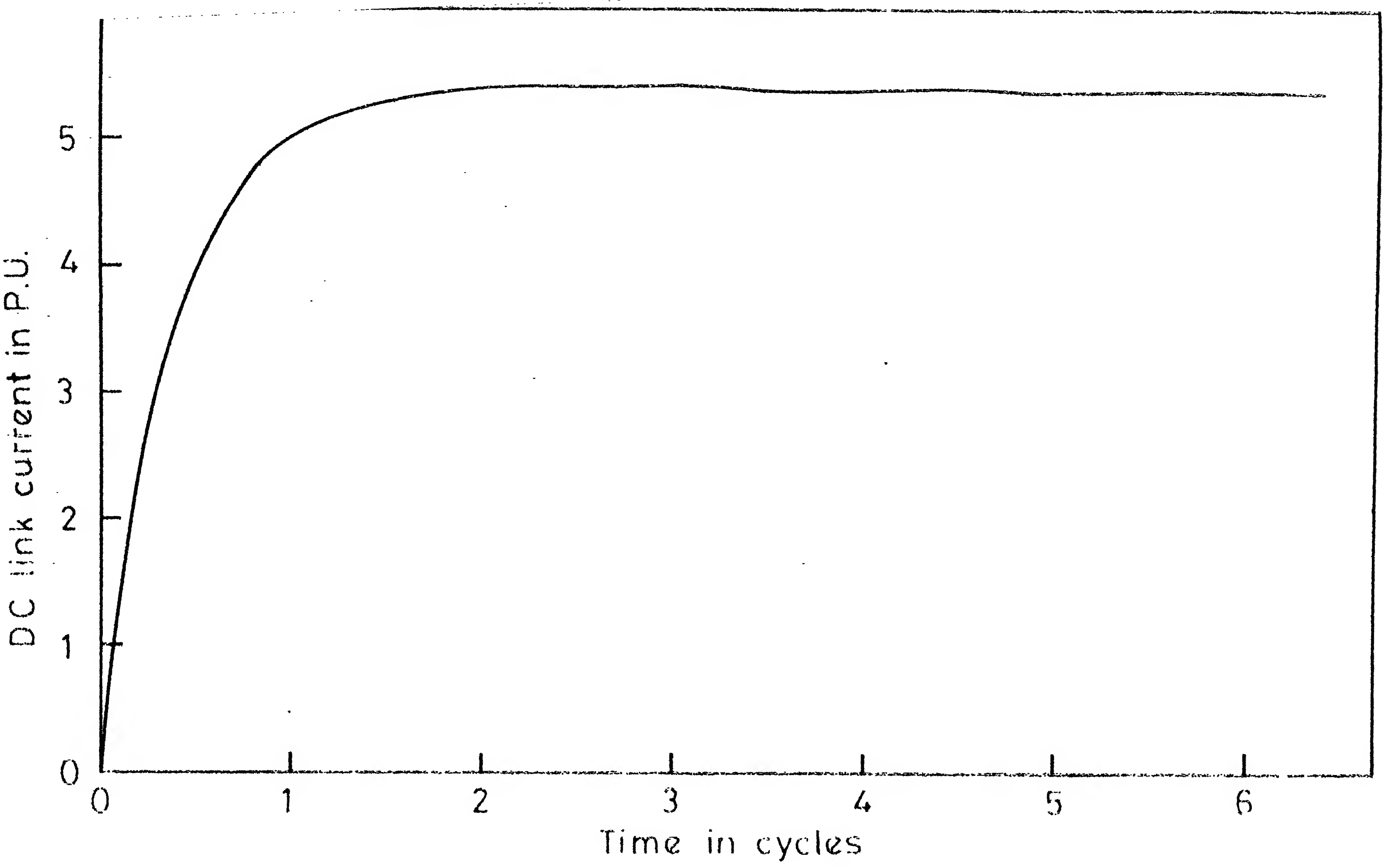

Fig. 3.3 - Transient response of DC link current.

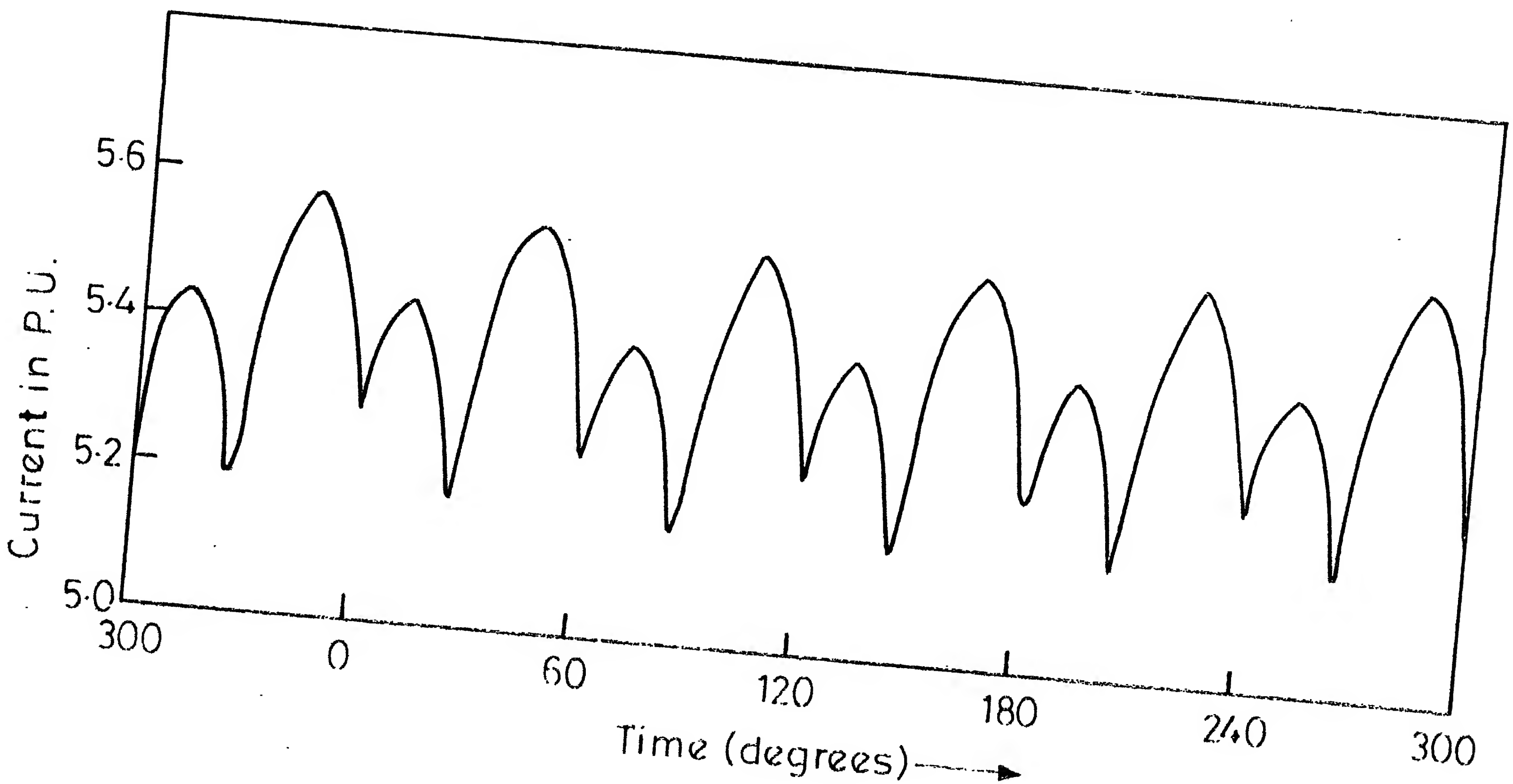

Fig. 3.4 - Direct current wave form.

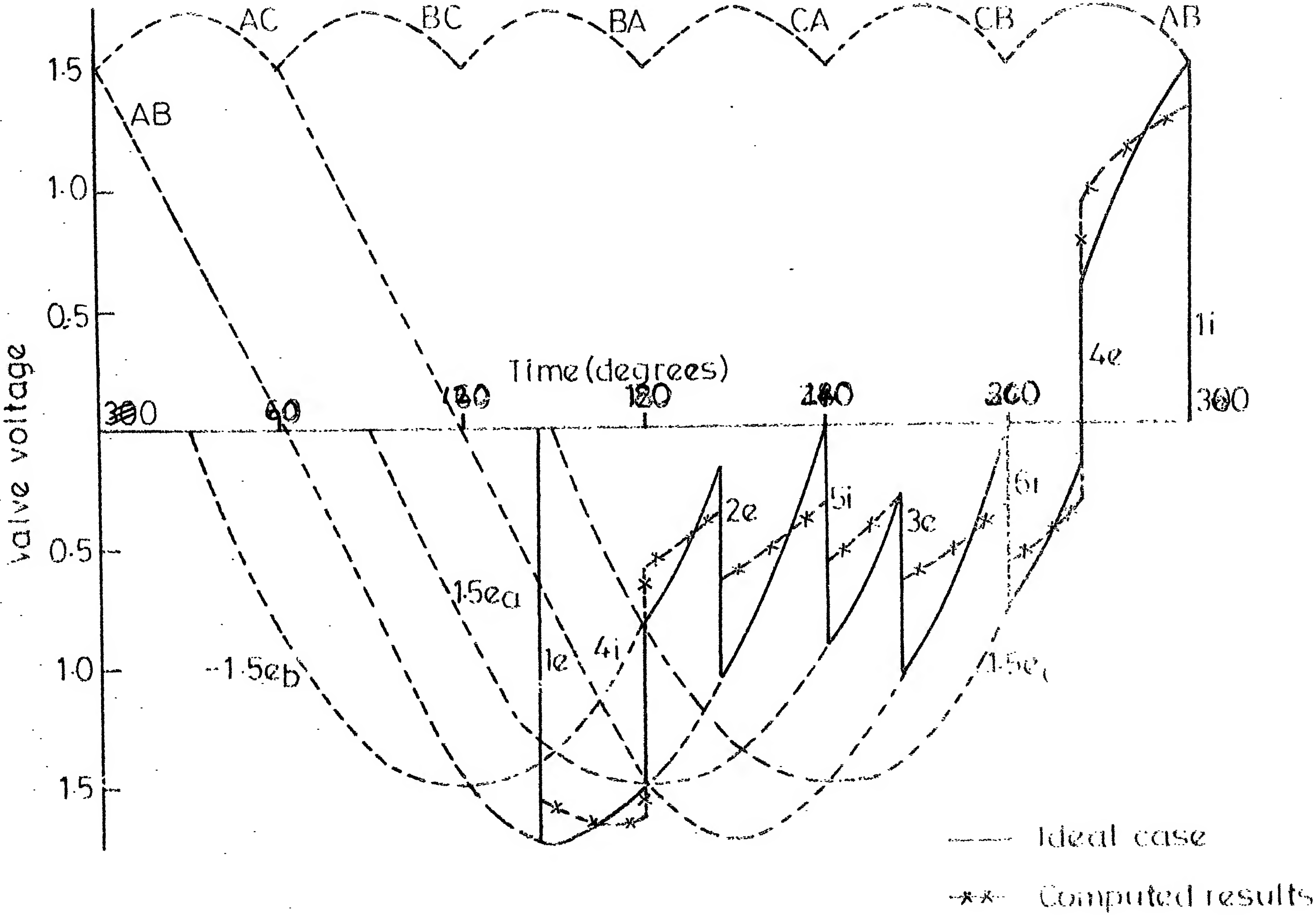

Fig. 3.5 Voltage across valve 1.

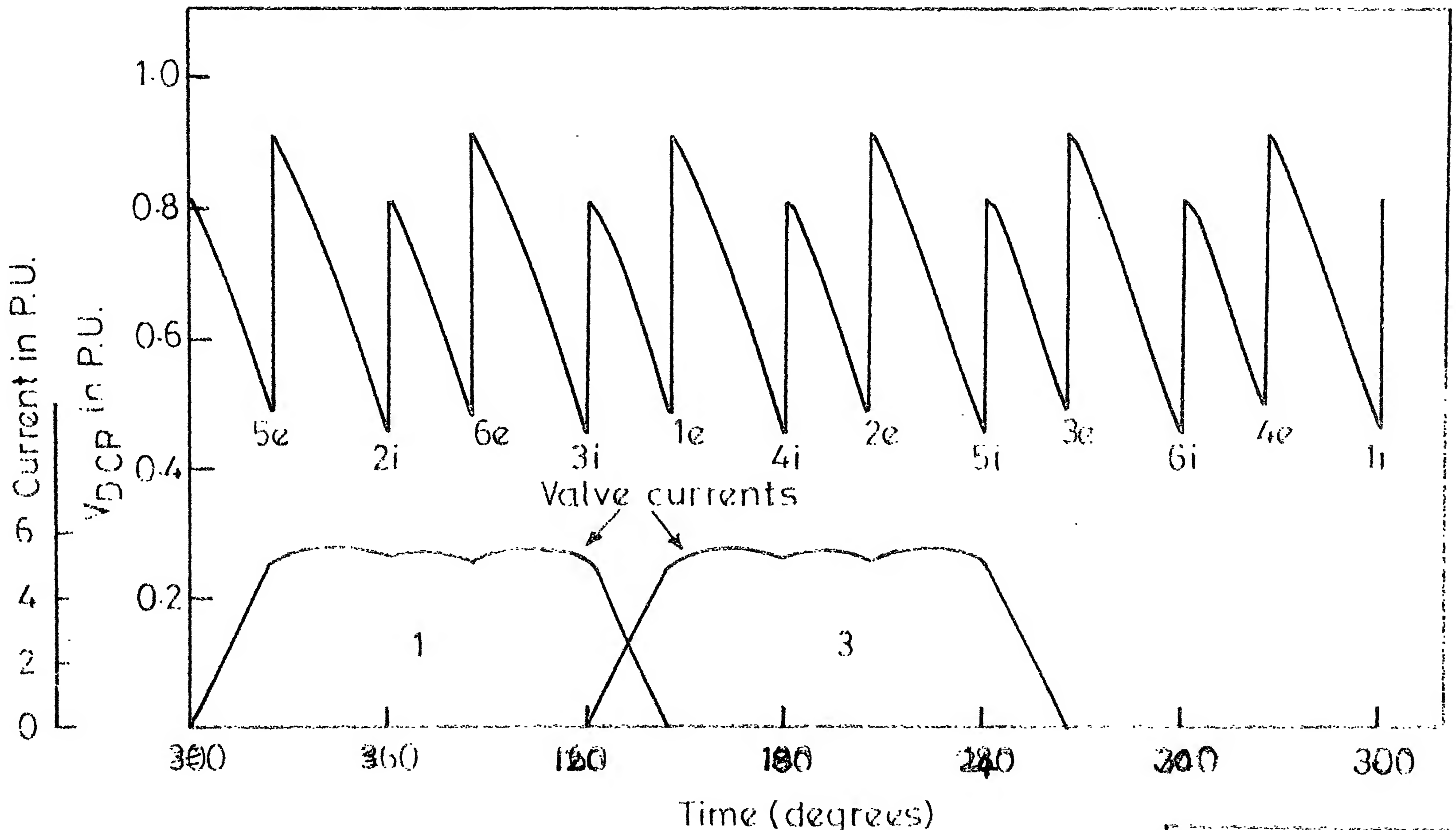

Fig. 3.6 - Steady state rectifier terminal voltage, steady state valve currents.

Note:
1i - valve 1 Ignites
1e - valve 1 Extinguishe

3.4 CONCLUSION

Digital computer program is developed for the simulation of a 3-phase bridge converter based on the mathematical model given in Chapter 2. This is applied for the transient analysis of a converter feeding into a dc voltage source. The steady state waveforms of the various quantities such as valve voltages and currents are also presented and compared with theoretically calculated waveforms which are obtained with the assumption of ripple free direct current.

The example presented in this chapter involves only the consideration of the normal 12 modes of the converter operation. The next chapter will present examples that involve abnormal operation of the converter.

CHAPTER 4

HVDC SYSTEM SIMULATION UNDER FAULTED CONDITIONS

4.1 INTRODUCTION

The faults in DC system can be classified as faults on DC line and faults in converters. The variations in DC link current because of faults on the DC line can be controlled by controlling the firing instants of valves. The rapid control of current is necessary as the overcurrents can lead to commutation failures of the inverters and damage to valves. Commutation failures in inverters are generally selfcuring. Only under certain serious faults, the converters have to be blocked and bypassed.

The faults on DC line are not considered in the present work but only the phenomena of commutation failure and continuous misfire in inverter are studied.

4.2 SIMULATION OF HVDC SYSTEM

The entire HVDC power transmission system considered for the present study is shown in Fig.4.1. For simplicity single 'T' network is considered to represent the transmission line. The mathematical model for the single converter used in the previous chapter can be duplicated for the two converters with the voltage source replaced by the capacitor voltage. Treating the two converters separately for a short interval, the two sets of equations can be interlinked by the following equations

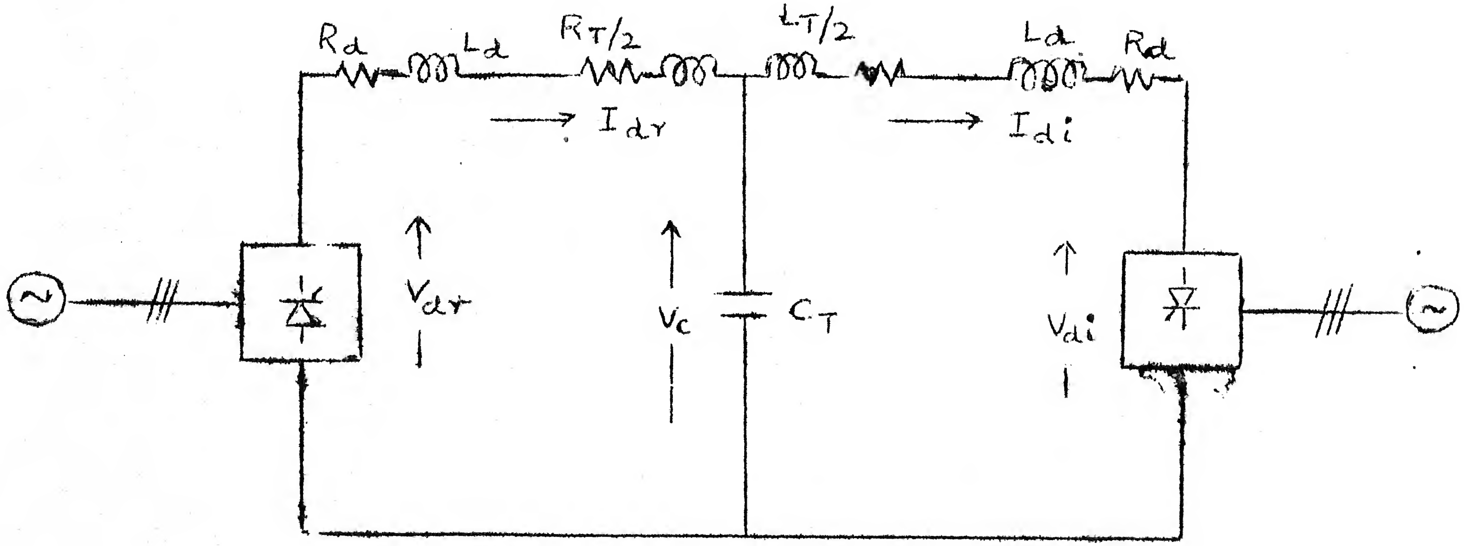

FIG. 4.1. HVDC POWER TRANSMISSION SYSTEM

$$pV_c = (I_{dr} - I_{di})/C_T \tag{4.1}$$

where C_T, I_{dr} and I_{di} are shown in Fig.4.1.

The system data is taken from ref.7 and is given below.

AC system and transformer representation for each converter:

Resistance per phase	= 0.5 ohms
Inductance per phase	= 20 mH
AC system frequency	= 50 Hz
AC system voltage (L/N)	= 42.8 kV

Transmission line parameters:

Equivalent series resistance	= 2.16 ohms
Equivalent series inductance	= 13 mH
Equivalent shunt capacitance	= 21.6 μF.

For the present problem the value of smoothing reactor (L_d) is taken as 1.0 H and the resistance (R_d) is taken as 0.05 ohms. The firing angles for the valves in rectifier and inverter are taken as 15° and 150° respectively.

Operation of the HVDC system is simulated with the following initial conditions:

Capacitor voltage Vc	= 90 kV
DC link current	= 650 Amps.

It is observed that the system reached steady state in 46 cycles (0.92 sec.). This high settling time is obviously

due to the large value of smoothing reactor, but to reduce the ripple in the direct current, the value of L_d is taken as one henry.

After allowing the system to reach steady state, two disturbances are simulated - 1. commutation failure in the inverter and 2. continuous misfire in the inverter. Both the examples are presented in the following section along with the results obtained.

4.3 EXAMPLES

4.3.1 Commutation Failure: Commutation failure is the most common misoperation of inverter. It is not a fault of the inverter but results mostly from causes that are external to the converter bridge. Commutation failure is the failure to complete commutation before the commutating emf reverses. It takes place because of a sudden reduction in AC voltage or late ignition of valves. The effect of a commutation failure is to reduce the bridge voltage to zero for a short period during which the valve currents may increase due to discharge of the line capacitance. A single commutation failure is selfcuring particularly when aided by the constant extinction angle controller. Cascading of commutation failures is to be avoided to limit the overcurrents on DC link. In double commutation failure, there is a time period when the inverter voltage reverses resulting in overcurrents on DC line.

In the present example a repetitive double commutation failure is observed due to the sudden reduction in the AC voltage at the inverter. Under steady state conditions the AC voltage at the inverter end is 42.8 kV (L/N). This is suddenly reduced to 15 kV (L/N) and the observed results are shown in Figs. 4.2 and 4.3, with and without changes in valve firing angle.

Results and Discussion: Fig.4.2 shows the variations of

a) Direct current at inverter terminals (I_{di})

b) Capacitor voltage (V_c)

c) Inverter terminal voltage (V_{di}).

The purpose of the present simulation is to study the commutation failure in inverter with and without the changes in valve firing angle. The results in Fig.4.2 are observed when there is a reduction in the AC voltage at inverter station. This reduction is introduced at the end of the first commutation period in the 48th cycle. As a result the instantaneous terminal voltage is suddenly decreased from 85.3 kV to 26.9 kV (point P_1). At this stage valve 5 and 6 are in conducting state. At point P_2 valve 1 is fired. The portion of the curve from P_2 to P_3 indicates the unsuccessful commutation and valves 5, 6 and 1 are in conducting state. At the end of this period valve 2 is fired and the terminal voltage collapsed to zero as four valves (5, 6, 1 and 2) are

conducting. Before reaching point P_4, valve 1 ceased to conduct, thus a short circuit on DC link is still maintained by Valves 5 and 2. At P_4 valve 3 has to fire but did not fire because of the zero voltage across it. At P_5 valve 2 ceased a 5 and 6 are in conducting state. Here the point to be noted i the double commutation failure (valve 5 to 1 and valve 6 to 2) in the inverter. Eventhough the combination 5 and 6 is a norm one, as it occurred in the abnormal portion of the cycle, the terminal voltage V_{di} became negative remained negative till th end of that cycle. Because of this negative voltage valve 4 did not fire and the change in the state of the converter occurred only when valve 1 is fired at point P_6. P_6 corresponds to P_2 of the previous cycle and the same phenomena is repeated. Because of no current control action and the discharge of capacitor when V_{di} is zero, the direct current increased at a fast rate and reached 2200 amps in two cycles after creating the disturbance. It is to be noted that the initial steady state value of the current is 630 amps.

Fig.4.3 shows the variation of the DC quantities under control action at the inverter. Here the valve firing angle is also reduced simultaneously with the reduction in AC voltage at inverter station. The firing angle is reduced from 150° to 110° and an improved system response is observed. It can be noted that the occurrence of repetitive

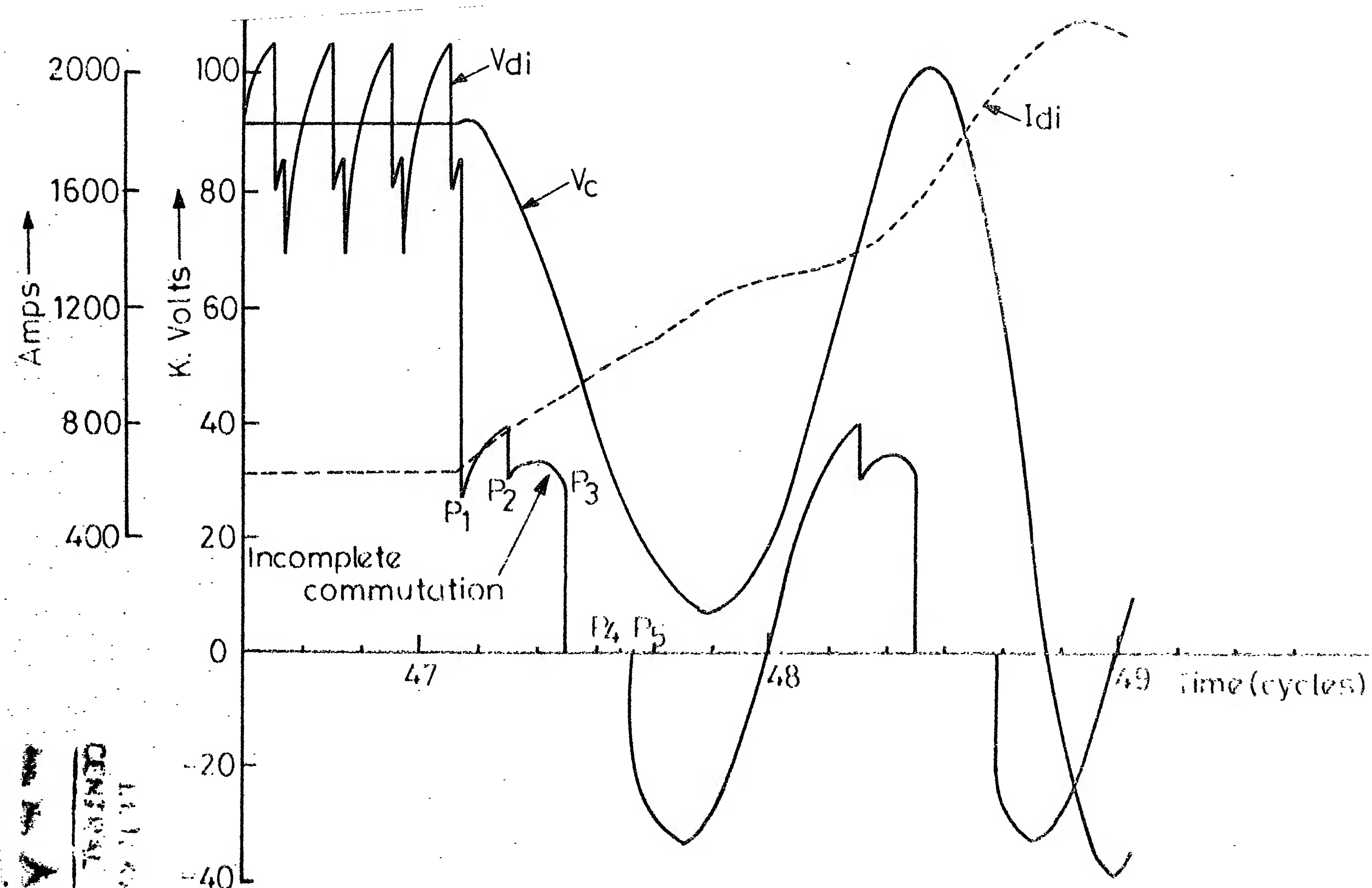

Fig. 4.2 – Double commutation failure due to reduction in AC voltage.

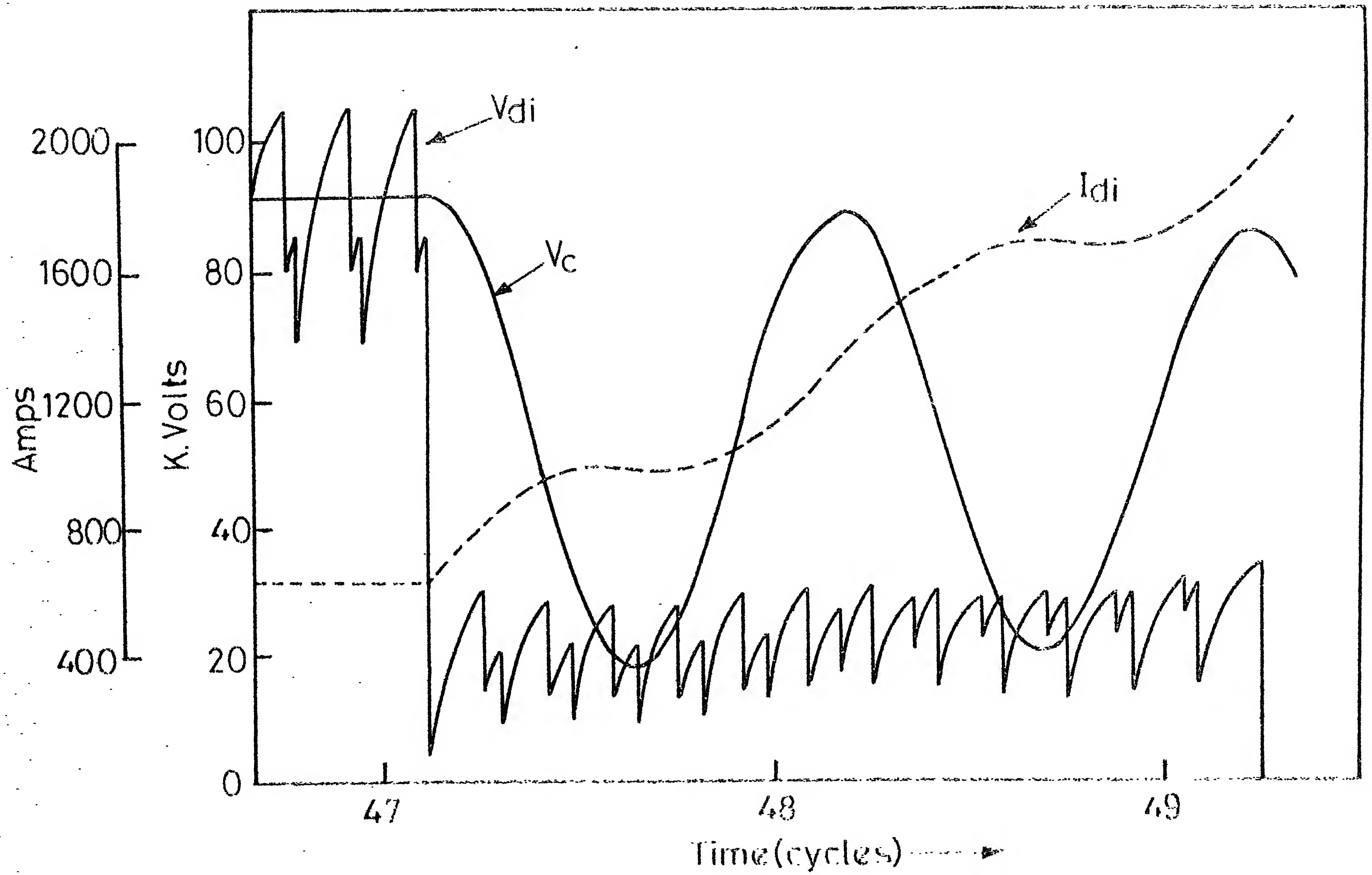

Fig 4.3 Simultaneous reduction of α - improved response

double commutation failure is avoided and direct current increased at a slower rate.

4.3.2 Misfire in Inverter: Misfire is the failure of a valve to ignite. In thyristor valves which are suitably designed, misfire will not occur unless there is a malfunction in the firing control scheme. During this fault also the dc voltage of the rectifier bridge is reduced to zero, but for a short duration. This appears once in a cycle and may persist for many cycles depending upon whether the cause is temporary or permanent. Continuous misfire of inverter valves is a serious fault and it impresses AC voltages on the DC line.

Continuous misfire of the inverter valves is simulated by inhibiting the firing pulses to all the valves at the time when valves 5 and 6 are conducting. The results obtained are shown in Figs. 4.4 to 4.8.

Results and Discussion:

Figs. 4.4 to 4.8 show the variations of the following quantities:

a) Direct current at rectifier terminals (I_{dr}).

b) Direct current at inverter terminals (I_{di}).

c) Capacitor voltage (V_c).

d) Inverter terminal voltage (V_{di}).

e) Rectifier terminal voltage (V_{dr}).

From Figs.4.4 and 4.5, it can be noted that the line current became oscillatory and a maximum of 8500 amps., at

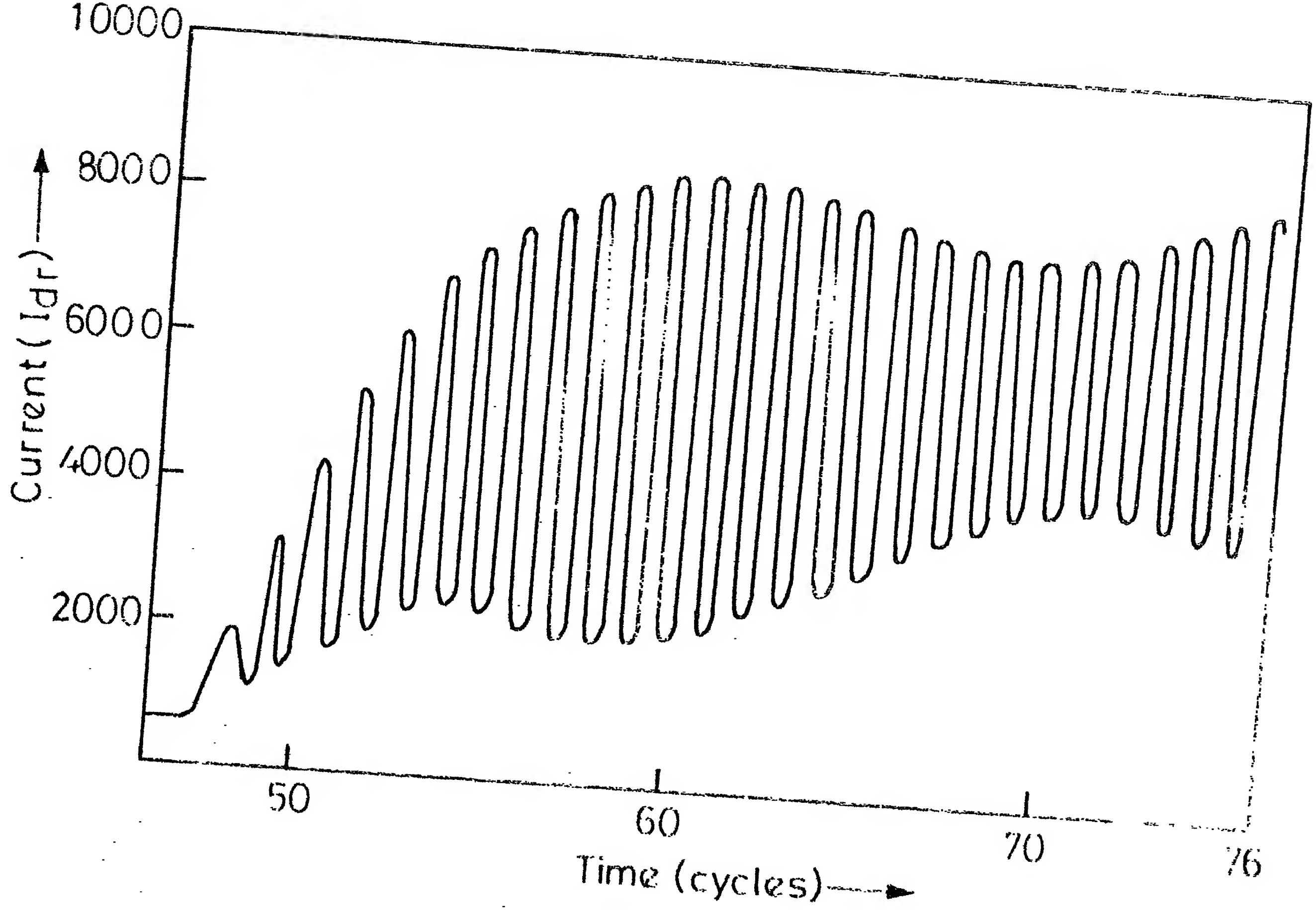

Fig. 4.4 - D C Link current at rectifier terminals.

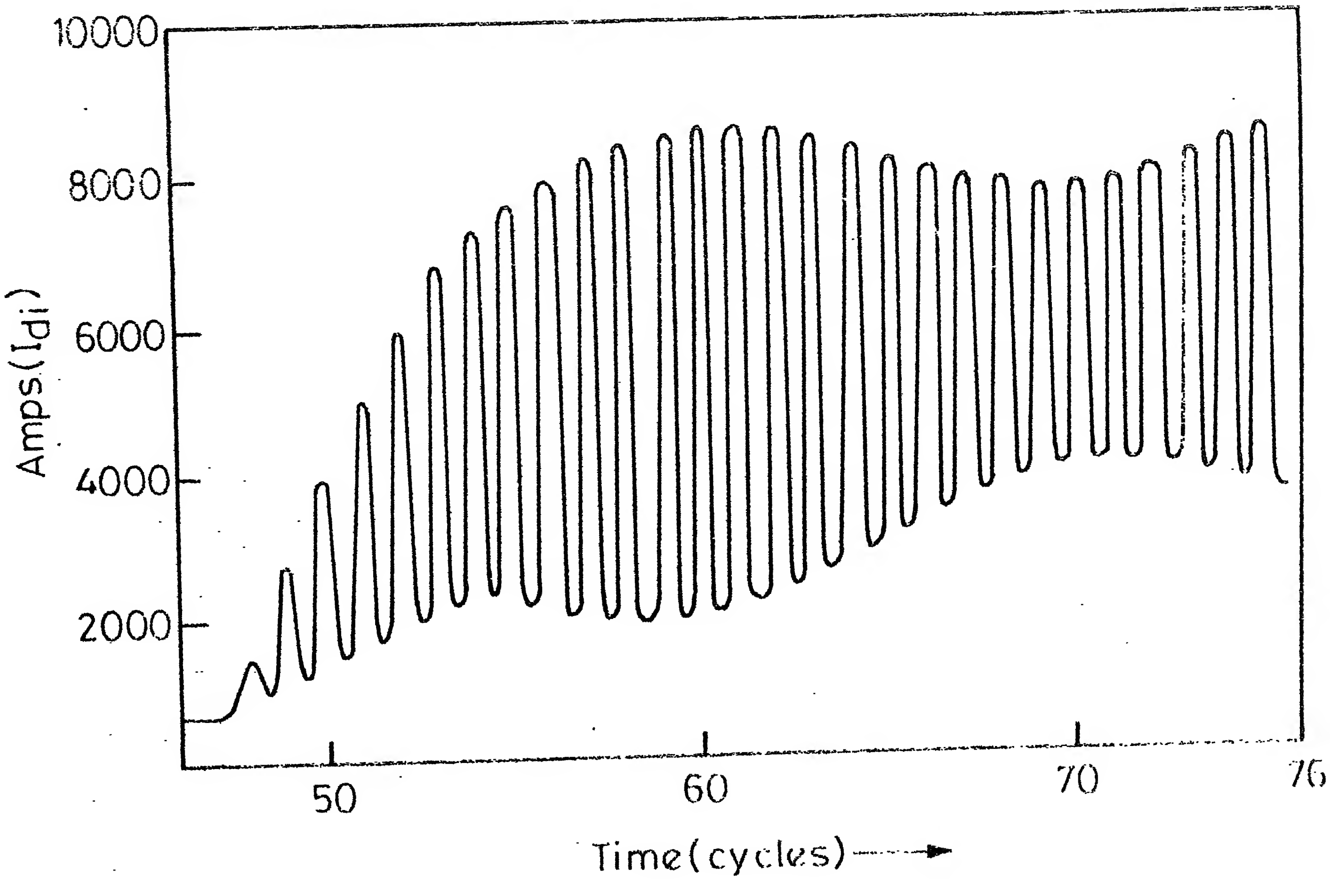

Fig. 4.5 – D C Link current at inverter terminals

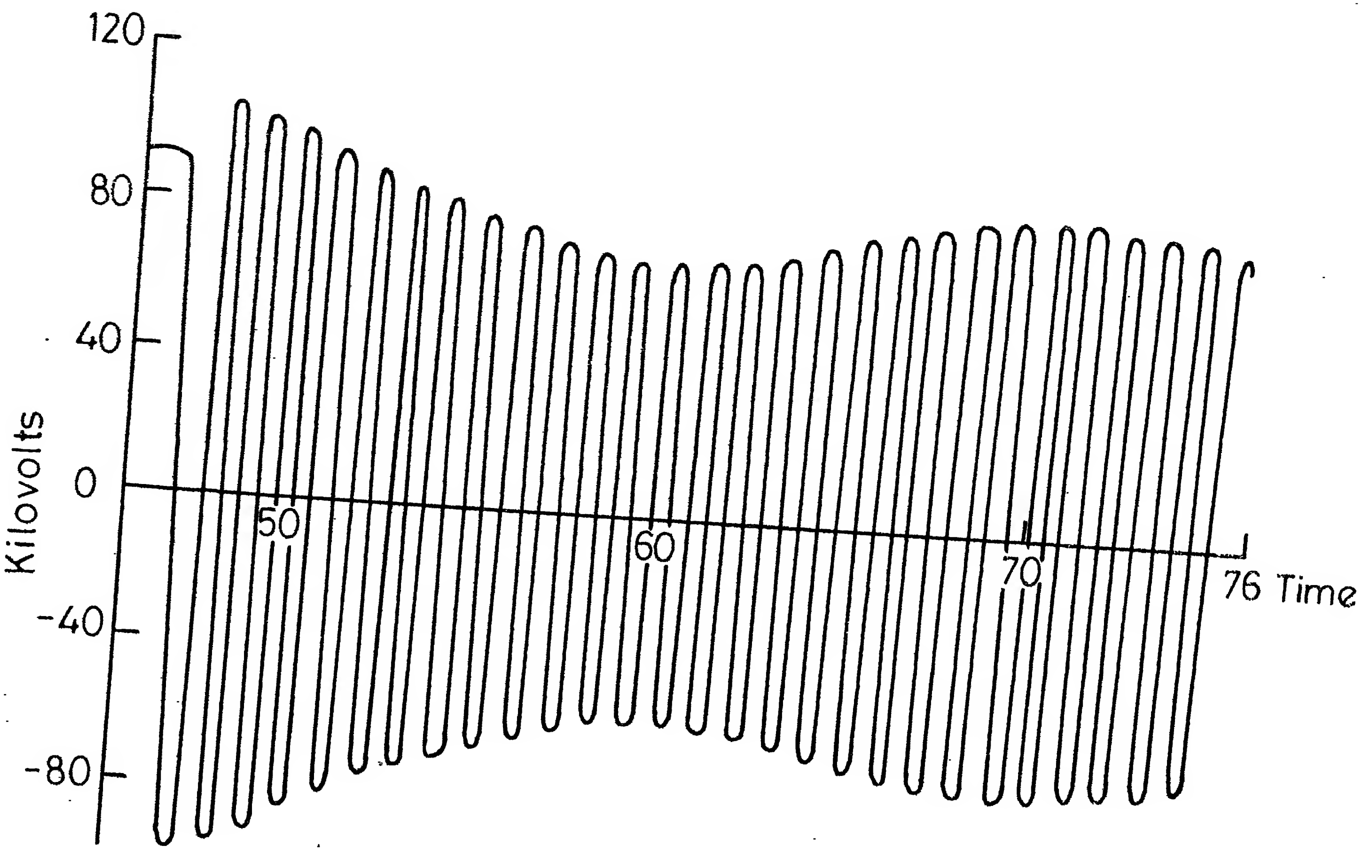

Fig. 4.7 - Inverter terminal voltage.

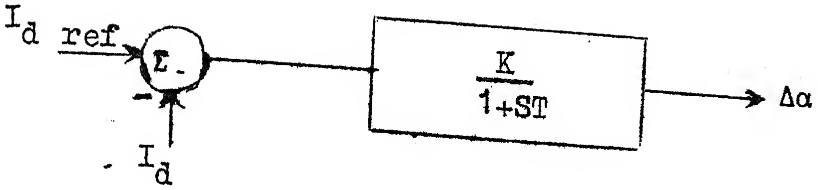

Fig.4.9 Simplified Control Scheme.

If the measured current (I_d) is less than the current order ($I_{d\ ref}$), the controller advances the firing of the valve (decreases the firing angle), thus raising the rectifier internal voltage, thus leading to increase in I_d. If the measured current is greater than the current order, controller increases the firing angle so that the internal voltage decreases and hence I_d.

From the above discussion, it is clear that k should be negative. The following values for k and T are chosen arbitrarily for this simplified scheme.

$$k = -0.1, \; T = 1.0.$$

The current order I_{dref} is taken as 630 amps., the steady-state current observed from the previous examples. The following equation can be easily derived from the above block diagram.

$$\frac{d}{dt}(\Delta\alpha) = \frac{1}{T}[(I_{dref} - I_d)k - \Delta\alpha] \qquad (4.2)$$

$$\alpha_{n+1} = \alpha_n + \Delta\alpha \qquad (4.3)$$

where n represents the cycle number.

To implement this scheme it is necessary that eqn.(4.2) is to be solved simultaneously with the other equations defining the state of the system. In this simulation α is updated every cycle starting with the valve number 2 by using the equation (4.3).

Assuming the steady state conditions in the beginning the commutation failure and continuous misfire in inverter are simulated and compared with the results in the previous section.

Results and Discussion:

i. Commutation failure: Fig.4.10 shows the variation of

a) direct current at inverter terminals (I_{di})

b) capacitor voltage (V_c)

c) inverter terminal voltage (V_{di}).

The effect of control scheme seems to be negligible in the first two cycles and there is not much difference observed in the results presented in Figs. 4.10 and 4.2.

ii. Continuous misfire: The steady state conditions are taken as initial conditions and valves 4 and 5 are made to conduct through out the cycle, by inhibiting the firing pulses to other valves. The results are given for 15 cycles after the creation of this disturbance at the end of which the DC link current became discontinuous at the rectifier end.

Figs. 4.11 to 4.13 show the variations of

a) Direct current at inverter terminals (I_{di})

b) Capacitor voltage (V_c)

c) Inverter terminal voltage (V_{di}).

It can be observed from Figs. 4.11 and 4.5 that the inverter terminal current reached a maximum of 6557 amps., whereas it reached to 8610 amps in the same time in the absence of control. Correspondingly a decrease in the line voltage is also observed, and can be concluded from Figs.4.12 and 4.6. The maximum voltage observed on the capacitor is 803 kV in the presence of control and 988 kV in the absence of control. The current controller has little effect on the DC voltage at the inverter terminals.

4.4 CONCLUSION

In this chapter HVDC system is simulated using the computer program developed in the previous chapter and two cases of misoperation of inverter valves are studied. In particular a study of the overvoltages and overcurrents on DC line caused by 1) commutation failure and 2) continuous misfire in inverter is made. In the first example a double repetitive commutation failure is observed due to a sudden reduction of AC voltage at inverter station. This created overcurrents on DC line. These overcurrents are controlled and the system performance is improved by reducing the firing angle of the inverter valves. As second example, continuous misfire in

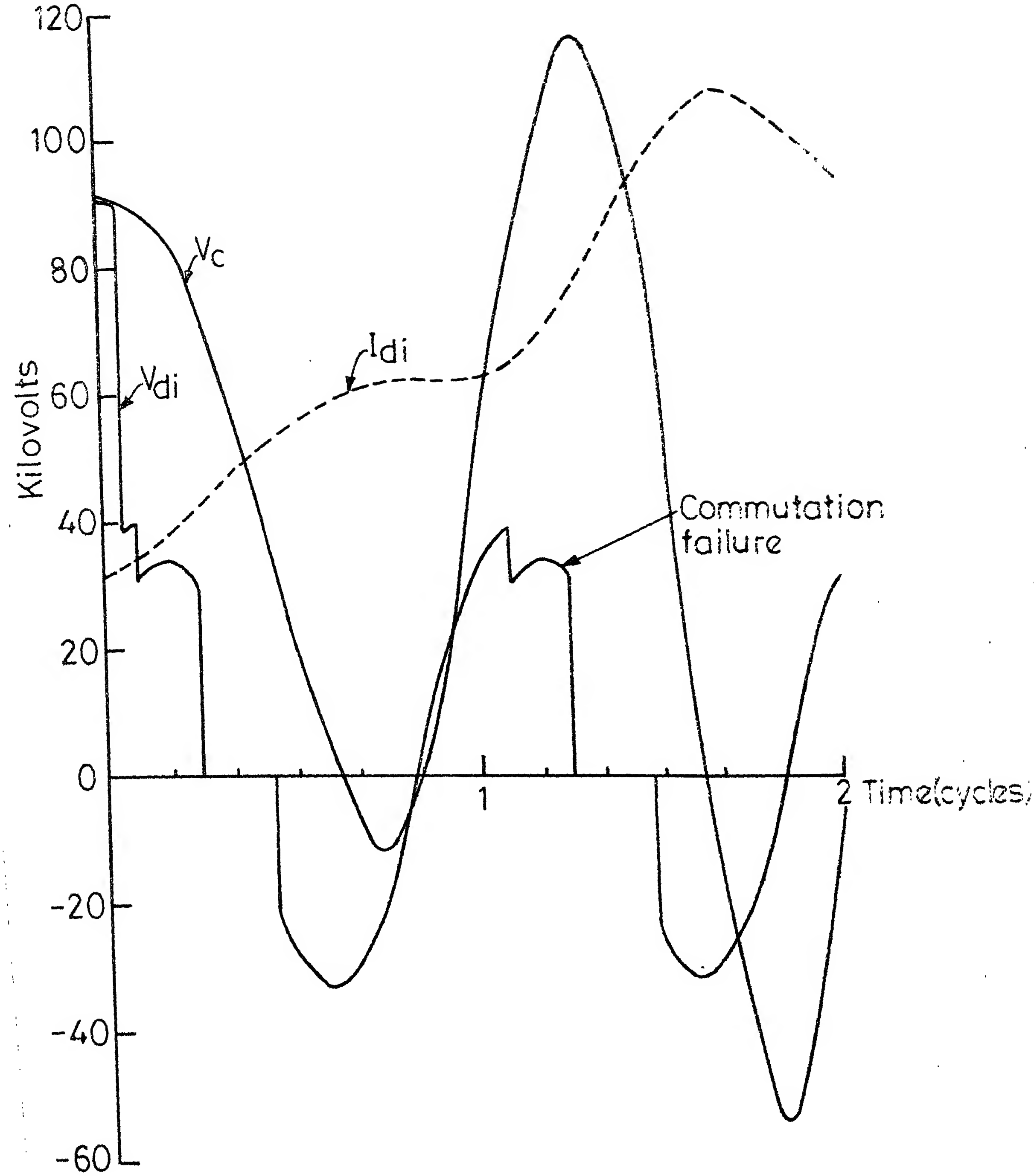

Fig. 4.10-Commutation failure (with control).

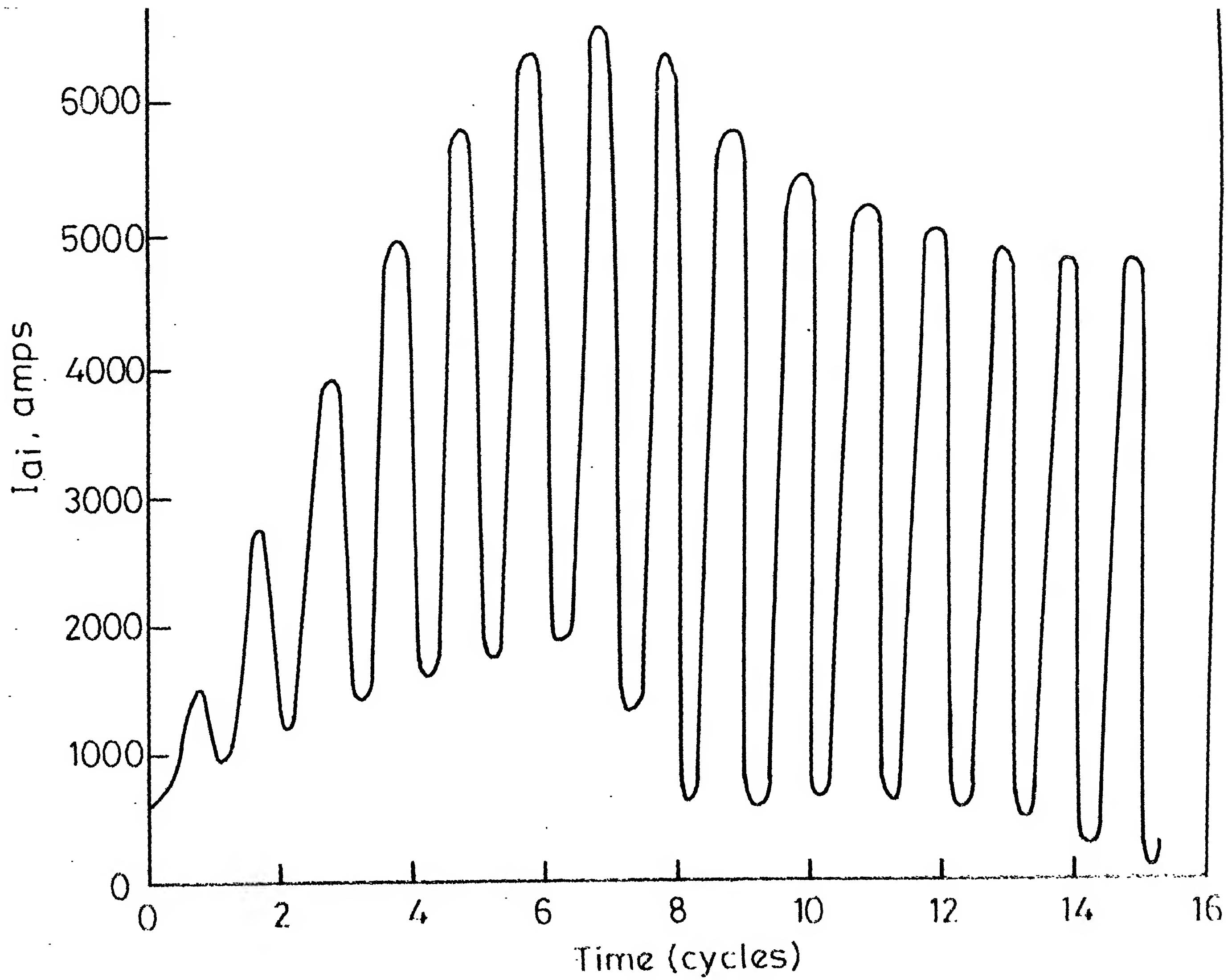

Fig. 4.11 – Direct current at inverter terminals (with control).

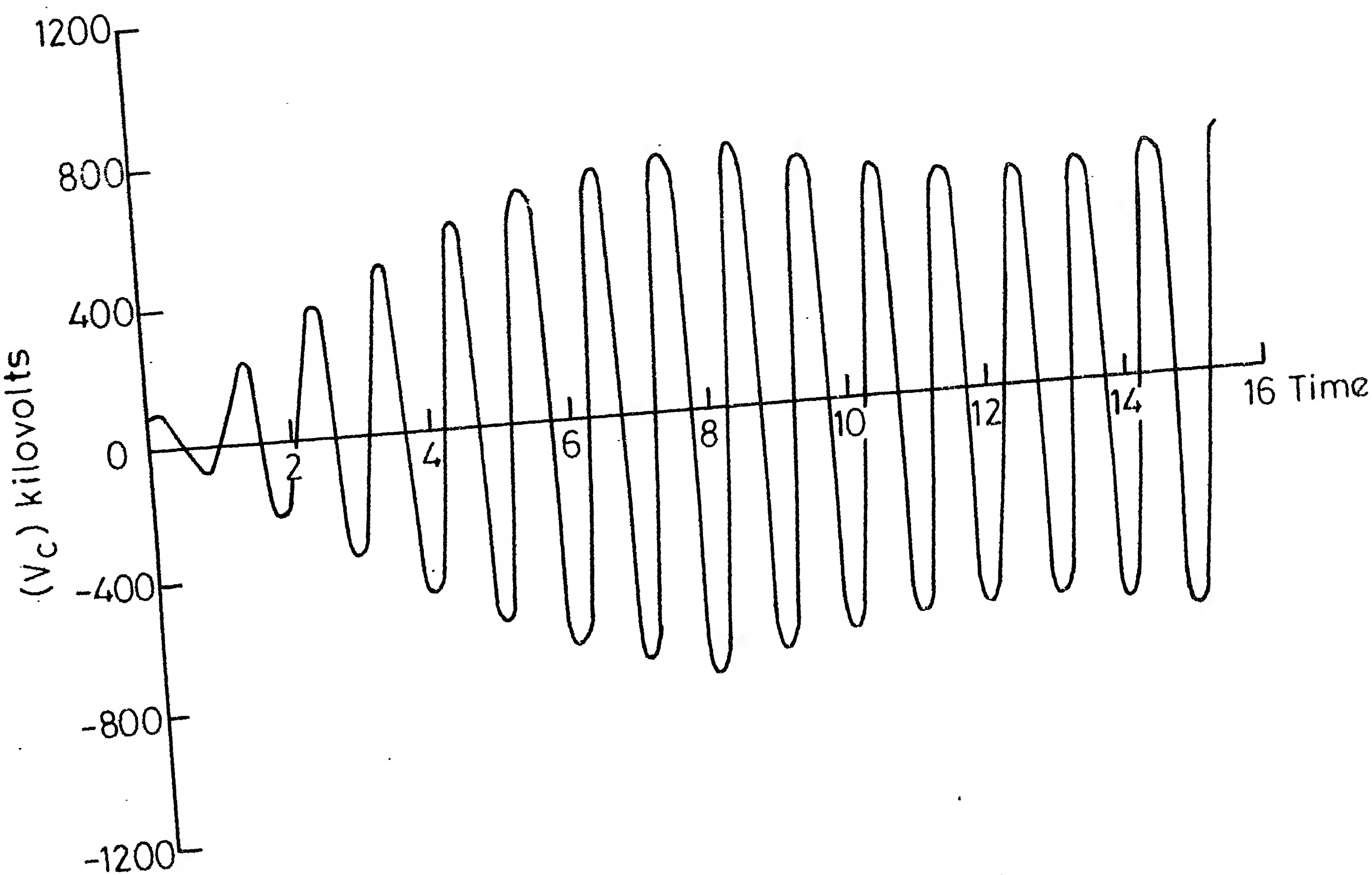

Fig. 4.12- Capacitor voltage (with control).

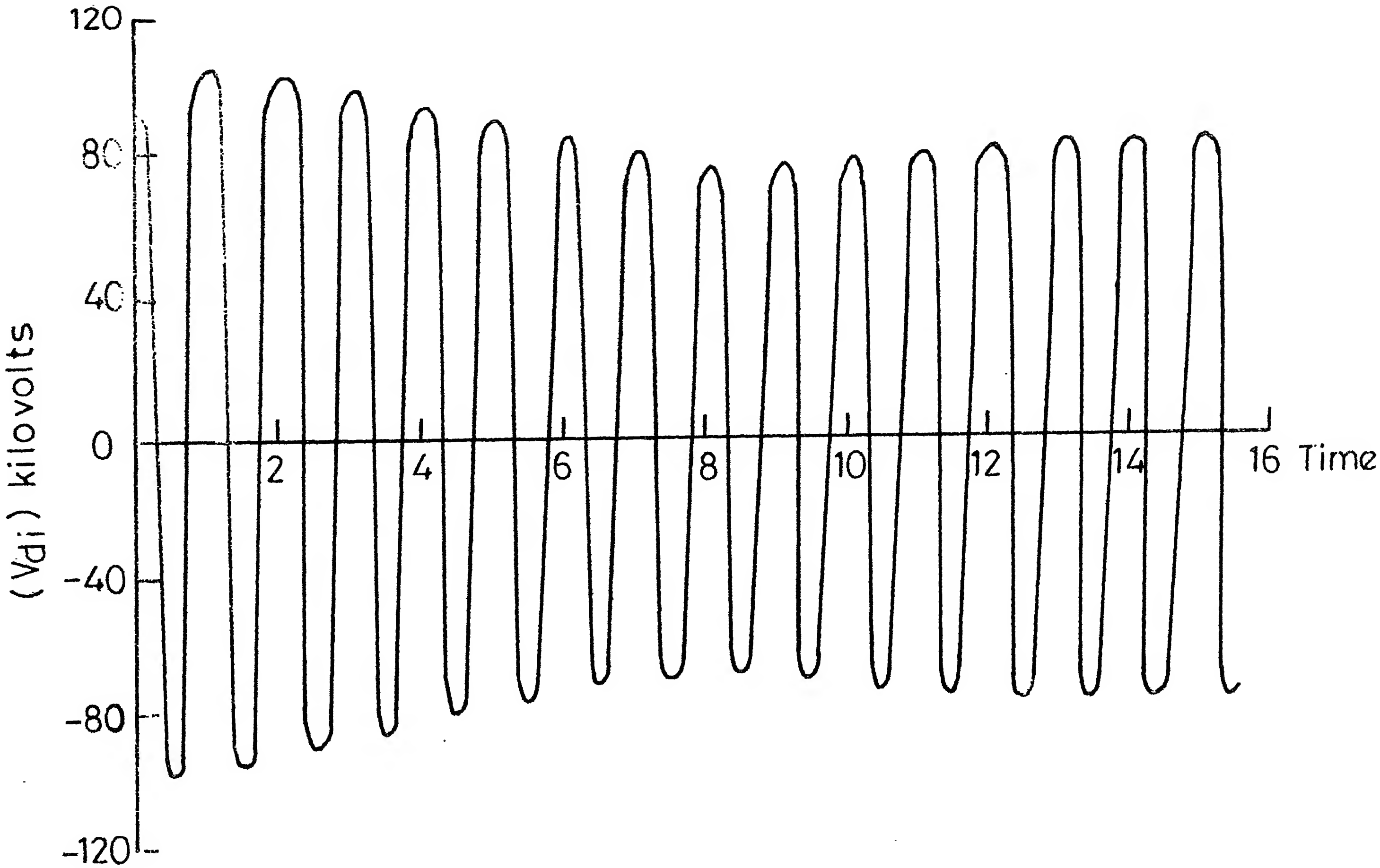

Fig. 4·13 – Inverter terminal voltage (with control).

the inverter, which leads to severe AC voltages on DC line is considered. This can be mitigated to some extent using a current controller at the rectifier.

An attempt has been made to simulate the action of current control at the rectifier using a simplified scheme. The values of the gain and the time constant are chosen somewhat arbitrarily and it is observed that with this controller, the overvoltages and the currents are reduced in the case of misfire of inverter valves. The current controller has little influence on the commutation failure at the inverter as this event occurred within very short time after the disturbance (reduction in AC voltage).

CHAPTER 5

CONCLUSIONS

5.1 SUMMARY

The dynamic simulation of the bridge converter is extremely difficult because of its varying topology, caused by the commencement and cessation of valve conduction. No simple methods are so far available in the literature.

In this thesis an attempt has been made to simulate the complete range of operation of the bridge converter on a unified basis. For this purpose a detailed mathematical model is developed in Chapter 2. A computer program based on this is utilized for the transient analysis of a single converter. Later a HVDC power transmission system, consisting of two converter stations, is simulated to study the overcurrents and overvoltages in the system caused by commutation failure in the inverter and misoperation of inverter valves respectively.

In this thesis the approach adopted for simulation is along the lines given in ref.11, but the basic equations are derived on the basis of topological considerations. In ref.11, the authors did not consider the smoothing reactor. They analysed only the normal operating modes and hence the abnormal modes corresponding to the faulted conditions cannot be simulated. These modes are also considered in the present

simulation, utilizing the generalized equations for the abnormal modes.

5.2 SCOPE FOR FURTHER WORK

The simulation procedure used in the present work can be greatly improved, if a suitable technique, to directly formulate the equations for a given mode from the basic equations derived in Chapter 2, is adopted. The simulation should be in such a way that no preformulation of differential equations defining the converter state is needed.

In simulating the HVDC transmission system, for simplicity a single T network is used to represent the transmission line. It is not a difficult task to consider several T sections, if greater accuracy is required or very long lines are considered. This will simply increase the number of equations to be solved. The inclusion of filter circuits and valve damping circuits is an extensionto the present work, but would not alter the basis of the program. It is to be noted that the representation of valves by ideal switches is not possible when considering the behaviour of the system at high frequencies.

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